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This report describes the experience gained and lessons learned from the ongoing field evaluations of seven small, 2- to 20-kW wind energy conversion systems (WECS) at Navy installations located in the Southern California desert, on San Nicolas Island, in California, and in Kaneohe Bay, Hawaii. The field tests show that the WECS's bearings and yaw slip-rings are prone to failure. The failures were attributed to the corrosive environment and poor design practices. Based upon the field tests, it is concluded that a reliable WECS must use a

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20. Continued

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METRIC CONVERSION FACTORS

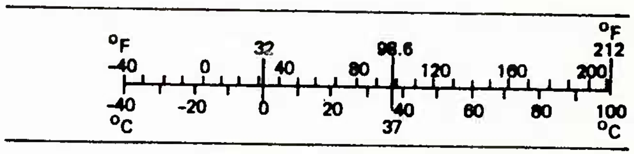
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2,000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1,000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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INTRODUCTION

The Naval Civil Engineering Laboratory (NCEL), as the lead laboratory for the Navy's Wind Energy Program involving shore facilities, has been investigating using wind power at Navy installations. The program's objective is to provide the design, reliability and availability, operating and maintenance, and cost information needed to develop guides, manuals, and procedures for using small wind energy conversion systems (WECS). Navy Public Works (PW) and Engineering Field Division (EFD) engineers must have information dealing with design, operation, maintenance, and cost of WECS installations to determine the feasibility of a WECS installation. If an application is economically feasible, appropriate designs, and installation and procedures must be available.

Over the past 12 years, efforts have been underway in the United States, England, West Germany, Denmark, The Netherlands, and France to develop small-capacity (up to 60 kW) wind-driven turbine generators with low-rated windspeeds (below 20 mph); these designs were economical at most locations (Ref 1 through 4). At the present time, over 50 manufacturers are producing small WECS with rating from 1 to 60 kW (Ref 5). The main problems associated with the WECS industry today are the lack of mass production and the meager amount of data on reliability and maintenance characteristics of the systems. Because of the variable nature of the wind, most WECS operate at variable rotational speed and power output. The power conditioning method and hardware for converting the generator's variable output to match the electrical characteristics at remote sites and power distribution grids of Navy bases are still going through evolution. Field tests were, therefore, planned to collect operating and maintenance data on various sizes of wind-driven turbine generators, and to develop methods and hardware needed for utilizing variable output of the wind turbine generators. This report describes the results of various ongoing small WECS field tests, including the lessons learned from operating such power systems.

REVIEW OF PRESENT TECHNOLOGY

Two basic types of wind turbines exist on the market today: those with a horizontal-axis rotor and those with a vertical-axis rotor. There are first and second generation vertical-axis wind turbine (VAWT) designs available in the size 1-to 25-kW range. The VAWT technology is still in its early stages of development. The horizontal-axis wind turbine (HAWT) technology has advanced to third and fourth generation designs, which are showing excellent on-line system availability on California wind farms. Most surveys have also confirmed the HAWT's superior operating characteristics, efficiency, and cost (Ref 6). Hence, the scope of the Navy's effort in wind energy has been limited to the HAWTs.

The components of the small WECS can be broken into several subcomponents. They are:

a. The rotor blades and hub assembly capture the energy of the wind and convert it to torque and rotational speed.

b. The transmission steps up the rotor's rpm to match the generator's rotational speed.

c. The generator converts the mechanical energy to electrical energy.

d. The control system governs the wind turbine for maximum efficiency and protection.

e. The tower elevates the turbine above total ground level into winds that are undisturbed by the ground's features.

The wind system suitable for Navy application must operate reliably for long periods of time, perform safely, and produce energy on a cost-effective basis at locations with moderate to severe corrosion environments. The demand for a reliable operation over extended periods (25 years or more), coupled with dynamic loading of WECS components due to a turbulent atmosphere, subject the materials to their fatigue limits. Next, the presence of moisture and salt in the atmosphere results in poor lubrication of WECS bearings. Thus, numerous trade-offs and decisions must be made by designers and manufacturers of WECS concerning rotor configuration, control systems, tower shape and type, material choices, etc. Some of the design considerations necessary for reliable WECS are discussed next.

Rotor Blades and Hub Assembly

The rotor blades and hub assembly are used to convert the wind's kinetic energy into useful torque and shaft power. Several design considerations that are extremely important for an efficient and reliable rotor are:

a. Number of blades
b. Material of blades
c. Variable-pitch or fixed-pitch blades
d. Taper and twist of blades
e. Protection of blades against high gusts

The small WECS horizontal-axis, designed for generating power, usually uses two- or three-blade rotors. A two-bladed rotor is lighter and less expensive than a three-bladed rotor; however, the latter vibrates less and has a more stable system operation. Recently some manufacturers have started using two-bladed rotors with a teeter to minimize the excessive vibration.

The rotor blades are manufactured from materials such as laminated wood, steel, aluminum, fiberglass, or carbon composites. Wooden blades generally have a superior fatigue strength with an extremely high modulus of rupture with a magnitude of over 16,000 psi. Unlike their metal counterparts, woods and fiberglass are less susceptible to corrosion. Metal and fiberglass (with metal mesh) tend to increase the problem of electromagnetic interference for rotor blades greater than 25 feet in diameter.

Some manufacturers control rotor rotational speeds by allowing the blades to pitch above a certain rotational speed. This, however, results in a lower system reliability because additional bearings and controls are needed in the rotor hub. Other manufacturers design their rotor blades with various degrees of twist and taper, which results in a more efficient WECS. The blades are often constructed from steel, aluminum, carbon composites, or fiberglass; but the extra efficiency gained by using a more sophisticated air-foil is offset by the increased cost and difficulties with fabricating the blades.

Some WECS designers achieve increased blade life by allowing the blades to have some pliability. When a gust or gyroscopic force from sudden yawing occurs, the blades can flex slightly to absorb the extra energy. This results in less stress and longer blade life. Using a teetering rotor can increase the blades' life span as well.

Transmission

The type of transmission used in a WECS varies from one machine to the next. In most of the machines on the market, the transmission, in the form of a gearbox, is used to increase the rotor's speed to match the generator's operating speed ranges. The transmission can also help absorb the axial thrust from the rotor assembly. Several small WECS presently available employ multi-pole, direct-drive generators to eliminate using gearboxes for increased system reliability. In other machines, the transmission is used to change the direction of the torque. This is done so the turbine is free to yaw in the wind while the generator is fixed vertically to the tower. A bevel gear is used to change the direction from the horizontal axis of the wind turbine to the vertical axis of the generator. This setup increases the WECS's reliability because slip-rings and yaw bearings are not needed between the generator and the power conditioning system.

Generators

The generators suitable for WECS include conventional DC generators, alternators, or induction generators. Although conventional DC generators are commercially available and well understood, a major drawback is their dependence on brushes; and selecting brushes is not a scientific process. Brushes are subject to wear and must transfer high electrical currents. Localized heat, caused by bar-to-bar voltage as the brush moves over the commutator, also causes wear. High currents in the rotating armature in a low-voltage machine also lead to manufacturing difficulties as heavy-duty wires must be inserted in the slots. The armature wires are subjected to centrifugal forces that result in friction. Due to potential

of arcing at various electrical points, using DC generators for Naval application can lead to electromagnetic interference (EMI) problems as well.

The alternators currently available include permanent magnet, lundel rotating field, and conventional laminated rotor. These alternators have several advantages. The permanent magnet alternator does not require field slip-rings or brushes. For the lundel or laminated rotor, only a field current is transferred and there is no bar-to-bar voltage variation over the smooth slip-ring surface. Laminated rotors have smaller wires in slots than the DC generator, but are still subject to the centrifugal forces and friction. The lundel has one coil wound around the central shaft in the shape of a solenoid rather than one coil per pole; hence, stresses in operation are in tension.

The permanent magnet alternator has several advantages: no magnetizing field losses, the best theoretical efficiency at the rated rpm, and no field slip-rings on the rotating shaft. Several disadvantages include: it is difficult to magnetize the magnet, assembly problems, cogging losses, overspeed-voltage control, and reducted flux density by temperature extremes.

The advantages of the lundel alternator include: easy to regulate in overspeed conditions, casting materials are available, and easy to assemble and manufacture. The disadvantages include: lower efficiency at a rated speed and the stack diameter to the length ratio limitations.

The conventional laminated wound rotor has several drawbacks including: high power requirements, it is difficult to manufacture, and the centrifugal forces that act on the windings.

Some manufacturers are designing small WECS with induction generators. These generators must have a grid at the site for their operation and, hence, are not suitable for remote applications. In addition, these systems sacrifice efficiency by operating at a less than optimum constant rotor rpm. Stand alone capability and rotor efficiency are greater in an equivalent-sized WECS that uses variable-speed alternators.

Control System

The control systems on a small WECS operate to give maximum efficiency output and protect against adverse conditions. These systems can include yaw control, blade pitch control, and automatic overspeed protection.

Yaw Controls. The yaw control design required depends on the type of WECS. Two HAWT systems are available: upwind and downwind. An upwind systems' rotor is located upwind of the mounting tower and requires some type of arrangement to yaw with the wind direction. A downwind system's rotor is situated downwind of its mounting tower and is self-yawing. Though this design does not require an external yaw drive for steering into the wind, the rotor, due to the downwind arrangement, experiences additional wind turbulence produced by the supporting tower.

The upwind system does not need a yaw system. The most common yaw system is a downwind tail (either a vane or rudder). The tail is also used to turn the rotor away from winds higher than the system's design

windspeed. The tail overspeed protection is automatic on some small WECS but is manual on others. The automatic operation of the WECS overwind protection control is accomplished by an external wind measuring system (an anemometer and a winch). Turning the blades out of the wind, however, allows them to be driven by the wind in two different angles of attack per revolution. This means the mechanical forces exerted on the blades are reversed twice during every revolution, thus, resulting in blade fatigue and possible failure.

Free-yawing systems react instantly to sudden wind changes. Because of the inertial-gyroscopic effects (P-factor) generated by a running rotor, tremendous forces and stresses are generated on the blades. This results in fatigue on the blades and hub assembly that can lead to failure. For these reasons, some European countries have prohibited free-yawing small WECS. An available alternative is to use extra small rotors on the sides of the small WECS that start running when hit by a side wind. These rotors are down-geared some 2,000 to 4,000 times before yawing the system. The result is a slow-yawing small WECS with minimal gyroscopic forces. This arrangement increases the system reliability.

Blade Pitch Control. Blade pitch controls the speed and improves efficiency. Two common methods of controlling blade pitch are mechanical and hydraulic. Using loaded bars attached to the hub assembly is a simple method of controlling blade pitch. As the speed of the wind increases, the rpm of the rotor increases. This increase of rpm causes an increase in the amount of centrifugal force on the bar, which causes the pitch to increase. Pitch increase contributes to the efficiency of the rotor. If the wind is blowing faster than the cut-off velocity, the increase in pitch reduces the rotor rpm. The pitching of the rotor blades is synchronized to minimize a dynamic unbalance that could ultimately result in failure.

A hydraulic control available on the market uses an actuator with an oil reservoir to control the pitch. The blades are initially at full pitch. As the wind turns the rotor, a pump on the rotor axle fills an oil cylinder that leaks oil back to the reservoir at a constant rate. As the oil cylinder fills, the oil pressure increases and the pitch decreases. The faster the wind, the more oil is pumped; the greater the oil pressure, the less the pitch. An additional sensor for high speed drains the cylinder and idles the rotors. Another vibration sensor provided in the system also drains the cylinder and idles the rotor during severe vibrations.

Several methods of rotor overspeed protection in high winds are necessary to ensure the system's safety. Basically, three methods commonly used for overspeed protection are:

a. Feathering the blades fully.

b. Turning the rotor assembly 90 degrees out of the wind either vertically or horizontally.

c. Using some type of braking system.

To fully feather the blades requires some type of blade pitch control, but this method is better than the other two methods mentioned, as there is less dynamic force on the blades. The advantage of turning the blades 90 degrees out of the wind is that when the wind slows down to the useful range of speed, the small WECS can automatically realign itself. On some systems, the blades can still be active while producing power in higher windspeeds.

A centrifugally activated air brake and a conventional brake, located on the drive train, are two types of brakes that are common on the small WECS. The centrifugally activated air brakes are located on the tips of the rotor blades. As the rpm of the rotors increase, the centrifugal force on the air brakes causes the rotors to oppose the revolution of the blades, thus effectively decreasing the rpms. The conventional brake is used to stop the rotor from spinning and is usually set manually. This brake stops the small WECS during high winds or while performing repairs on the small WECS.

Towers

Towers raise the WECS into the undisturbed airflow. The correct tower height is determined by the clearance needed for the rotor and what effect the surroundings has on the airflow. The following items should be considered before selecting a tower: the amount of force (both static and dynamic) exerted by the WECS, how easy is it to erect, and how easy is it to install or remove the WECS. The frequency characteristics of the tower must be checked with the operating frequency of the small WECS to minimize dynamic linkage between the two. Several types of towers used with the small WECS are:

a. Wooden pole (tubular, open-truss tower, guyed)
b. Concrete tower (free-standing)
c. Wooden pole (tubular, open-truss tower, free-standing)

The guyed tower requires a larger amount of space for its free-standing counterparts due to the guy wires. If the tower is hinged at the bottom it can be installed with a winch and A-frame (see Figure 1). Installing and removing the small WECS can be done on the lowered tower. If the tower is fixed, a large crane will be needed to install the tower. This implies that a crane is available, which is not always possible. Guy wires that are also prone to corrosion (see Figure 2). They must be checked periodically for proper tension.

The free-standing concrete tower uses less space that the guyed tower, but a crane is needed to install and remove the small WECS. The free-standing tower can be hinged at the base for installing at remote sites and requires less space than the guyed tower.

Environmental Concerns

Several environmental concerns that should be addressed when designing or using a small WECS are:

a. High winds
b. Excessive rainfall
c. Saltwater spray
d. Dust
e. Ice
f. Hail
g. Lighting
h. Earthquakes
i. Electromagnetic interference (EMI)

High winds have been mentioned in detail in the preceding paragraphs. Excessive rainfall, saltwater spray, and dust can be remedied by making sure everything is sealed and all exposed metal is coated to prevent corrosion. Ice, hail, lightning, and earthquakes can occur and some precautions should be taken to prevent damage.

EMI is another concern that is more of a problem with placement of the small WECS than with it's design. The generator, due to the rotating magnetic field, does radiate electromagnetic signals, but, with proper shielding, this problem can be minimized. The tower and the blades, however, could block and/or reflect the electromagnetic waves that cause EMI.

Characteristics of small WECS-induced EMI are reflected for echo-type interference phenomenon produced by the small WECS support tower and nonrotating blades and a time-varying interference signal (multipath) in synchronization with the rotation rate of the blades. Amplitude-modulated (AM) wave forms are the most affected EMI from small WECS. The higher the frequency, the greater the interference.

EMI propagates in two directions from the small WECS (see Figure 3). The forward scattering affects receivers that have the small WECS located between them and the transmitter. This type of interference is caused by the shielding effect of the small WECS. The EMI also propagates backwards toward the transmitter. This type is known as specular scatter. This type of interference affects receivers located between a transmitter and a small WECS (see Figure 4). The most common effect of this type of interference in the television band is the presence of a moving ghost.

When a site and small WECS are selected, certain information is needed to determine the possible effects of EMI. They include:

a. Operating frequency of the radiated electromagnetic system.

b. Type of modulation used (AM, FM, PM, SSB, etc.).

c. Receiving antenna radiation pattern.

d. Type of data being sent (voice, digital data, etc.).

e. Physical size of support tower, wind turbine, and blade dimensions.

f. Rotating rate of wind turbine rotor.

g. Location of wind turbine with respect to receiver/transmitter.

h. Terrain surrounding small WECS and receiver installations.

With this information in hand, a person can determine whether the EMI is serious enough to warrant selecting a new site or a new type of small WECS, or both. To date, very little information is available on the EMI effects of WECS on military hardware operations.

Future investigations are needed to obtain and catalog the electromagnetic reflective properties of a wide range of small WECS blade material. In particular, models that include the effects of small WECS-induced EMI on specific signal transmitter and receiver operations at Naval installation must be developed. Such models of EMI characterization, together with the site's wind resource data, can be used to determine the correct site for small WECS installations at Navy bases. In other words, this information will enable an engineer to recommend a small WECS with maximum output and minimum EMI.

Power Conditioning Systems

Because of the wind's nature, the WECS tends to deliver electricity in varying voltages and frequencies. Most uses require electricity with constant voltage and frequency. Converting variable electricity to regulated (constant) electricity requires some type of power conditioning.

To decide what type of power conditioning is needed, a careful examination of the nature of the application is required. Two types of situations are prevalent. The first is a stand-alone installation. Power conditioning requirements vary with this type of installation. A remote site with a defined purpose and small-scale power requirements (e.g., operating repeater and radio beacons) can be satisfied adequately with a small DC-generating WECS with battery storage. The only power conditioning required for this installation would then be a voltage regulator. On the other hand, certain types of applications require more stringent power conditioning.

The second type of installation uses a WECS with the existing utility power grid. The power conditioning requirement for this type of installations are very rigid, but this type of installation is useful. The utility grid can act as a limitless storage medium by supplying power when the WECS is not meeting the needs of the load, or accepting power when the WECS is delivering more power than is needed. Some of this delivered power may be sold back to the utility company provided it is of good quality.

There are many concerns about connecting a WECS with the utility power grid. The most pressing concern is the quality of the power. Certain types of power converters introduce power degradation such as unwanted harmonics, reactive power, phase imbalance, and voltage flicker. In addition, there are concerns with safety, responsibility, and legal jurisdiction liability.

Four types of power conditioning systems are:

a. Automatic load matching
b. Synchronous solid-state inverter

c. DC motor-driven AC generators
d. Field modulation technique

These power conditioning systems are discussed in Reference 7.

Utility Concerns

Presently, there has been a proliferation of WECS being connected to rural electrical systems. They are generating concerns about the liability and power quality.

The question of liability is beyond the scope of this report, but if a WECS is connected to the utility grid, some questions must be answered. For example, who pays for the modifications of the utility equipment to allow cogeneration of power? Furthermore, who is responsible for the increase of cost and danger to the utility linemen?

The concern over power quality is very dependent on the power conditioning system used. Utility companies have stringent regulations concerning the amount of harmonics, reactive power, phase imbalance, and voltage flicker. In the past, energy flow has been strictly unidirectional from the utility company to its customers. Voltage could be regulated more easily. Any cause for the poor quality of power (some large industrial motors cause reactive power on the line) is usually corrected on an individual basis. This practice does not appear feasible for a large number of distributed energy sources. The power generated by WECS would have to meet the utility companies' quality requirements. This would increase the cost of power generated by the WECS.

Harmonic. When rotating machines become obsolete for conversion and inversion with the use of solid-state converters and inverters, the problems of harmonics in output wave form becomes more serious. Harmonics are the wave forms having frequencies that are multiples of the fundamental frequency (60 Hertz). As previously mentioned, inverters switching at the line frequency with line commutation have problems with harmonics. They produce a wave form that is not sinusoidal. This wave form is the sum of many sinusoids at higher frequencies. If the harmonic frequencies are in the television or radio frequency range, these frequencies could interfere with the television's or radio's reception. If these frequencies are in the audio frequency range and the telephone line is on the same pole of the distribution line, they could interfere with telephone's reception. Two possible solutions to these interference problems are to use an isolation transformer or a low-pass filter, but these systems will add to the cost and reduce the efficiency of the WECS.

Reactive Power. Both the line-commutated converters (because of inherent firing pulse delay) and the induction generator (because of the self-inductance/magnetizing delay) will have lagging characteristics. It is estimated that these devices have a power factor of 0.35 to 0.60 lagging. They require considerable reactive power from the utility in order to match utility grade power requirements. One possible solution is to install capacitors to supply reactive power.

Phase Imbalance. Utility companies deliver balanced, three-phase power. A single-phase WECS located on three-phase lines (if the WECS is large enough or in sufficient number) can cause phase imbalance problems. Such phase imbalance problems could cause starting problems (and excessive heating) of three-phase motors and possible neutral-to-ground voltages. It has been shown that neutral-to-ground voltage of even one volt can cause problems to Naval operation. A solution to this problem is to require all generators over a certain size generate three-phase power.

Voltage Flicker. The voltage flicker is caused by the induction generator drawing a large starting current to accelerate its inertia load. If the generator is connected to the utility line, this voltage flicker would be sensed by the other consumers drawings their power from the same line. The problem of voltage flicker could cause annoying phenomena, such as: striking television pictures, dimming lights, and malfunctioning of modern household appliances. This problem could be solved by insulating transformers at WECS locations or by installing additional pieces of soft-start equipment for the induction generator. This solution also adds to the cost of the power produced by WECS.

A highly recommended alternative to the expense in alleviating the quality power concerns for WECS is to operate these machines as energy conservation devices. By attaching WECS to loads where intermittency and quality of power are not important (e.g., mechanical applications, battery charging, electrical heating loads) and displacing the energy used for those applications at the retail rate, the WECS could deliver the full benefit of the wind without disturbing existing utility systems and without adding the expense of major power conditioning.

On the surface, interconnection with a utility grid seems to offer lower cost, but the institutional, technical, and economic problems associated with the interconnection of a WECS to a utility grid should be carefully considered. Although a majority of the WECSs currently being manufactured are designed for interconnection with a utility grid, many problems concerning safety, liability, metering, and undesirable interaction with the utility system can be avoided by choosing applications that do not require interconnection. Recently, due to a marked increase in utility-interconnected WECS, California wind farm companies have demonstrated the concerns raised previously are not significant to impact utility operations.

FIELD EVALUATIONS

NCEL selected certain classes of WECS that appeared suitable for Navy application. NCEL does not product test, but reviews generic categories to determine operating characteristics and idiosyncrasies. After the machine was purchased, it was taken to NCEL and the mechanical construction was inspected. It was then installed on a tower for a shakedown test lasting up to a year. During that time, engineers documented the machine's behavior in terms of daily operation, maintenance requirements, and reliability performance. The safety features were also carefully monitored.

Following the initial test period, the machine was then installed at a selected site for long-term demonstrations lasting from 1 to 4 years. These tests will develop detailed operational and maintenance data, reliability analyses, and economic information. Information obtained from these demonstrations will be included in the Wind System Application Guide for Navy Shore Facilities.

After the long-term test, the WECS (wind turbine generator, tower, power conditioning equipment, etc) may be turned over to the facility where the tests were conducted or moved to a new site for additional long-term testing under different wind conditions. This report describes seven field evaluations using various commercial wind-driven turbine generators. They include:

Generator Size	Test Location
2-kW	NCEL, Port Hueneme
5-kW	San Nicolas Island
6-kW	NS, Treasure Island and NCEL, Port Hueneme
9-kW	NWC, China Lake
10-kW	MCLB, Barstow
12-kW	Kaneohe Bay, Hawaii
20-kW	MCAS, Kaneohe Bay, Hawaii

2-kW WECS Demonstration at NCEL, Port Hueneme

For cost-effective wind-power generation, proper and full use of turbine output is extremely important. Most loads designed to operate on AC power require constant voltage for proper operation. In addition to a constant voltage requirement, some loads such as appliances and equipment with moving parts must have a synchronous 60-Hertz power supply. A variable-speed, rotor-driven generator with external voltage controls will deliver constant voltage synchronous power. If, however, such a wind turbine generator is used for heating loads, such as water heaters or a group of space heaters, the variable frequency power will not affect the load's performance. For such applications, a wind turbine generator with an automatic load-matching system (Figure 5) is adequate for wind-generated electricity. The load-matching system offers an inexpensive method of providing low-grade electrical power readily usable by heating loads.

A 2-kW WECS with an automatic load-matching system (Figure 6) for generator output use, is demonstrating various applications of wind power at NCEL's Advanced Energy Utilization Test Bed (AEUTB). The WECS facility is being used as a test bed for developing other uses of wind power.

The specification of the 2-kW WECS is shown in Table 1. This WECS consists of: a three-bladed, 12.5-foot-diam rotor, which drives a 2-kW brushless alternator through a gearbox. The WECS rotor, gearbox, and alternator assembly are mounted as one unit in a free standing, 60-foot-high steel tower. The 2-kW alternator is an eight pole, three-phase rotating field alternator that provides 220 volts of AC power. The DC power for the rotating field alternator is provided by a small AC exciter armature mounted on the same shaft. The exciter field is fed via a voltage regulator. The overspeeding of the wind turbine rotor in high winds and under a no-load condition is controlled by a centrifugal governor that changes the blade pitch angle, thus reducing the rotor's rotational speed. A magnetic latching device prevents the governor changing the blade pitch in windspeeds up to 30 mph. The performance characteristics of the WECS as a function of windspeed are given in Figure 7. The voltage versus windspeed plot of the WECS shows that at windspeeds greater than 10 mph the voltage regulator keeps the generator's voltage almost constant, and the value of the maximum voltage value can be varied by a potentiometer located in the regulator.

A wind plant was installed and connected (non-grid type) to the distribution system used for the lighting and water heating loads of the AEUTB. To date, the test data show excellent performance by the wind plant and the load matching system. As shown by the voltage versus windspeed plot, Figure 7, the load matching system improved the overall energy extraction from the wind. The wind plant facility has used wind generated electricity to operate: resistive-type space heaters, equipped with fans for circulation, and lights.

The 2-kW WECS generated approximately 376 kW-hr with an average windspeed of 7.7 mph between November 1983 and March 1984. The 2-kW WECS has been dependable thus far; however, some problems have occurred, especially with corrosion. The yaw bearing, steel blades, and slip-rings and bearings have all corroded. The 2-kW WECS, since its installation in 1977 at Port Hueneme, has suffered three failures of the slip-rings, two failures of the yaw bearing, and one failure of its blades-root bearing. The majority of the failure are attributed to the corrosive marine environment of the site. The slip-ring failures seemed to occur due to current leakage between the consecutive rings, which burned the plastic ring separators. Some of the failures were also caused by the brush holders breaking at the attachment-lug. The plastic ring failure could have been induced by moisture that generated arcing to the ground. In summary, the slip-ring failures were caused by poor design and poor weatherproofing.

A disadvantage of this machine is that it has to be removed from the tower to service the slip-rings and bearings. Future plans include continued testing of the plant at NCEL to demonstrate the cost-effective prototype hardware designed to improve energy utilization from small WECS.

5-kW WECS Demonstration at San Nicolas Island

A 5-kW upwind horizontal axis, three-bladed rotor driven, three-phase AC generator with an automatic load-matching device was installed and tested at San Nicolas Island (SNI). The 5-kW WECS at SNI (Figure 8) was used for space heating. Reasons for selecting SNI were its remoteness, present cost of energy, excellent wind condition, and its highly corrosive environment. The WECS's operational and performance data for space heating applications were collected through extensive field tests at SNI and two other sites, namely Port Hueneme and Laguna Peak.

The specifications of the 5-kW systems are given in Table 2. The WECS rotor has a centrifugal governor that increased the blade pitch as the windspeed increased to control the rpm. The WECS had a downwind tail to maintain orientation into the wind. In winds greater than 45 mph, the tail automatically turned 90 degrees to turn the rotor out of the wind. The WECS used a self-excited AC generator that required slip-rings for its wound rotating field. The 5-kW WECS, before being installed at SNI, was tested at Port Hueneme and Laguna Peak which have low and moderate wind regimes, respectively. To date, the test results indicate a poor availability of the WECS at SNI because of its highly corrosive environment.

A comparison of the WECS's performance based on the field data with the manufacturer's curve is given in Figure 9. Clearly, the field test results agree with the manufacturer's data over most of the operating windspeed ranges. Due to various failures of the WECS components at SNI, the results indicate that this site, in addition to being an excellent wind location, is also a highly corrosive marine environment for evaluating the WECS designs. The WECS was installed at SNI in November 1979 and following intermittent operation at this site, the system was retired in January 1984. The field tests at SNI furnished information for improving the WECS's reliability.

The WECS did not operate well because of SNI's environment. The main problem was that the bearings (Figure 10), slip-rings, electrical terminal, feathering controls, and voltage regulator corroded. The WECS rotor hub bearings showed corrosion of the race and false "brinelling" (rectangular dents). This type of bearing failure indicates excessive system vibration. This condition can be corrected by using proper lubrication. One attempt to improve the bearing's life under this environment was to fill the rotor hub with a lubricating oil that kept the bearing race coated with oil when the rotor was not turning, thus lubricating the wearing surfaces. This arrangement also prevented the bearing components from corroding because the salt and the moisture was trapped by the oil inside the hub. This design modification increased the mean time between failures (MTBF) from 90 to 280 days.

The 5-kW WECS used ordinary yaw slip-rings. Basically, there were three slip-rings mounted on the yaw shaft with the slip-rings separated by plastic spacers. The rings were connected to metal studs by pigtail connectors. The studs were insulated from the metal plate by placing plastic inserts around them. The moisture and the salt grounded the studs to the metal, causing arcing at various points of the slip-rings assembly. This was the most common cause of slip-ring failure during

the field test. The arcing also caused the brush holders in the pigtail connectors to corrode. The failures of the slip-rings can also be attributed to poor material choice and design.

Finally, in January 1984 the testing of the 5-kW WECS at SNI was stopped. The tests at SNI yielded the following information:

a. Performance and maintenance data on the wind plant and the load matching device under highly corrosive environmental conditions.

b. Design modifications needed to increase the system's reliability and subsequent availability.

c. Economics of such power systems for space and water-heating applications.

d. A WECS of this design requires frequent site visits (at least every 2 weeks) to ensure its proper operation.

6-kW WECS Demonstrations at Port Hueneme and Treasure Island

The 6-kW WECS chosen for this evaluation is identical in design to the 5-kW WECS discussed earlier. The only difference is that the generator uses a permanent magnet rotor. The 6-kW WECS installed at Treasure Island is shown in Figure 11, and the specifications are listed in Table 3.

The first Navy-wide use of a wind power system will be wind plants integrated with other power sources or grids to displace fuel or consumption of electric loads. Design information is needed for WECS before being installed at Navy facilities.

A synchronous inverter system provides one method of integrating a variable-output, wind-driven generator with another power source. When this evaluation was started, the synchronous inversion technique was still in its early stages of development, and data on the performance and reliability of such power conditioning were rather limited. The quality of power obtained from synchronous inverters using silicon control rectifiers (SCR's) for power transfer was also limited. The 6-kW WECS was, therefore, tested at Port Hueneme and Treasure Island to (Ref 8):

a. Demonstrate integrating a WECS with a base's power distribution system and assess any interconnection problems.

b. Determine the WECS's operation and maintenance in a corrosive environment.

c. Determine what design modifications needed to improve the WECS's power output and reliability.

d. Determine practicality of operating a small WECS under a field activity control.

e. Develop data on economics of wind power generation with this type and size WECS.

The initial testing of the 6-kW WECS at Port Hueneme demonstrated that the type of synchronous inverter used suffered from impedance matching. In other words, for the best performance of the WECS, it is extremely important to match its impedance with the AC generator at all windspeeds.

During the tests one of the problems encountered was to keep the synchronous inverter properly programmed to match its impedance with the AC generator at all windspeeds. A more efficient means of maintaining the inverter needs to be devised. One method for doing this is to have a variable trigger voltage for the SCR's.

The WECS did not perform well during the periods when the inverter was not programmed properly. The quality of power pumped into the distribution system is shown by the voltage and current waveforms shown in Figure 12. A comparison of the WECS's performance, based on field data and the manufacturer's curve, is shown in Figure 13. The comparison shows that the field results and the manufacturer's information agree.

The availability of the WECS at Port Hueneme was not good. Most of the downtime was caused by corroding slip-rings and electrical terminals, which led to arcing and failure. These failures were similar to the ones experienced by the 5-kW WECS tested at SNI. The WECS tested at Port Hueneme was done under close monitoring and supervision.

However, to test the WECS in an actual operational mode, it was moved to the Naval Station, Treasure Island, in September 1979. The 6-kW WECS was tested from September 1979 to June 1981 and yielded the following data:

a. Operation, maintenance, and performance of the 6-kW wind power system.

b. System availability and reliability.

Since the 6-kW WECS was installed, its performance has been satisfactory, with only two critical failures. The first failure occurred in late December 1979 and the second in early April 1981. Both failures were caused by arcing at the electrical terminals located on the yaw shaft, which caused grounding of the generator to the tower. The operating times before failure were approximately 120 days and 460 days, which corresponds to a system's MTBF of 290 days. Between 20 May 1980 and 10 March 1981, an interval of 295 days, 1,115 kW-hr of AC power was supplied by the WECS. This value corresponds to an annual output of 1,380 kW-hr. As shown in Figure 13, all of the test data for WECS performance at Treasure Island were taken at windspeeds below 20 mph. The field data show a mismatch of inverter impedance with that of the line at windspeeds greater than 20 mph. To measure WECS performance at higher windspeeds, it was moved to SNI where it worked for about 30 days and yielded good results. Due to the excessive corrosion of its components, the WECS was retired in January 1984. The performance data from SNI is shown in Figure 14.

The test results from the 6-kW WECS evaluation formed a basis for providing assistance to the field divisions in the application of wind power at Naval installations. Above all, the experience and data developed during the WECS demonstrations has enhanced the Navy's technical knowledge to implement wind power systems at Navy bases effectively.

9-KW WECS Demonstration at NWC, China Lake

The 9-kW WECS with battery storage, located at NWC China Lake, was evaluated for remote site stand-alone applications. The WECS employed a variable-speed, downwind rotor 32.8 feet in diameter with three variable-pitch blades. The blades were made of straight section extruded aluminum, each with a twisted and tapered fiberglass tip for high durability and efficiency of conversion. The blade pitch was controlled by a hydraulic governor in several stages:

a. High pitch for startup in 8 mph winds.

b. Constant pitch between startup to full power (8 to 20 mph winds).

c. Continuous pitch regulator to control rotor speed at full power in winds 20 mph or greater.

d. High wind shutdown in winds greater than 45 mph.

The rotor drove a low-speed, permanent magnet alternator without a gearbox. This arrangement resulted in high system efficiency and reliability. The entire rotor system and generator assembly was mounted on a 55-foot high, tiltdown, tubular tower for easy maintenance and repairs at this remote site.

The WECS installation is shown in Figure 15, and Table 4 lists the specifications. A voltage regulator was incorporated into the system for charging a deep-cycle, heavy-duty, lead-acid battery bank with a storage capacity of 112 kW-hr. A solid state constant frequency (60 Hertz) inverter connected to the battery bank supplied the load power requirements.

The system was installed at China Lake in September 1982 for checkout before being installed at Pinõn Peak for advanced demonstration. The manufacturer's performance curve for the WECS is shown in Figure 16.

Tests began in December 1982. Since this period, the wind turbine generator failed several times. The first failure occurred after 3 weeks of operation (early January 1983) when, due to arcing at the slip-ring, two of the collector brushes were damaged. Next, due to the blades flapping, the shroud around the hub assembly was damaged. The design modifications recommended by the vendor corrected this problem. Also, the overspeed control sensor for high-wind condition shutdown functioned improperly. The bearing hydraulic governor assembly failed. Figures 17 and 18 show the damaged shroud and its attachment braces. However, the weakest link in the generator is the hydraulic controller, which has an extremely poor reliability. The manufacturer is working to improve the hydraulic controller's design. As shown by the output versus windspeed curve of Figure 16, this WECS's performance has been excellent.

Some minor failures in the voltage regulator were experienced in January 1983, when arcing at the slip-ring was experienced. The vendor repaired the system and the system operated for approximately 20 days when the hydraulic actuator actuator malfunctioned again. The 9-kW WECS

tests at China Lake were discontinued and in May 1984 the WECS was relocated to Skaggs Island. The WECS will be generating in parallel with the distribution system with a line commutated inverter.

A new 16-kW system was selected for the NWC Piñon Peak site. It must be noted that throughout the field tests at China Lake, the inverters and batteries performed very well. The details of the 16-kW WECS demonstration at Piñon Peak will be covered in a separate report.

10-kW WECS Demonstration at MCLB Barstow

The WECS demonstrated at the Marine Corps Logistics Base (MCLB), Barstow, was of a commercially designed 10-kW wind-driven turbine induction generator. The reason for choosing this type of WECS was its low cost ($600/kW) and its simple design (because of its induction generator). The WECS used a three-bladed rotor 24.3 feet in diameter and was designed to produce 10 kW at a rated windspeed of 25 mph. The system was mounted on a free-standing, truss type steel tower approximately 40 feet in height. The WECS installed at MCLB is shown in Figure 19. The specifications of the WECS are listed in Table 5. The system was installed at Barstow in September 1982 and the tests began in October 1982. The system performed well until March 1983 with a maximum output of 8.5 kW in winds of 30 mph. A plot of the WECS's performance characteristics is shown in Figure 20. Clearly, the machine's performance was not as good as claimed by the vendor.

The WECS yawed freely with the wind's direction changes; the feathering control performed well by shutting the machine down in high winds and restarting it when the winds subsided. On 23 March 1983, the machine coupling failed, which resulted in the rotor free-wheeling in high winds, which caused the rotor to overspeed. Consequently, the rotor blades hit the tower and damaged it beyond repair (Figure 21). The damaged coupling, which caused the WECS's failure, is shown in Figure 22. The original WECS was replace with a new 10-kW WECS and the specification are listed in Table 6. The new WECS (Figure 23) was installed 24 May 1984 and is operational. The WECS is undergoing checkout tests and the details of the test will be included in a separate report.

For future applications of wind power at MCLB, an estimate of the long-term monthly and annual mean windspeed and power for Radio Hill was derived from data collected at that site and from nearby Elephant Mountain (Ref 9). The Radio Hill data consists of 6 months of data collected during 1981. The Elephant Mountain data consists of 16 months of data, collected during 1979 through 1981. The two stations were operating simultaneously during 3 months of 1981, and this link provided a means of relating the Radio Hill site to the more familiar site on Elephant Mountain. Elephant Mountain, located roughly 3-1/2 miles northeast of Radio Hill, is used as a reference to determine the long-term wind characteristics at Radio Hill.

The three columns in Table 7 give the estimated long-term monthly and annual mean values of windspeed, power, and energy pattern factor (EPF). The EPF, which is a measure of the variability of the wind, is defined as the mean speed cubed divided by the cube of the mean windspeed. A "normal" (Rayleigh function) distribution of windspeed has an

annual EPF of 1.93. EPF's well below 1.93 indicate a relatively steady windspeed, and vice versa. The minimum value is 1.00, which represents a constant windspeed.

The 1981 monthly estimated mean windspeed is illustrated in Figure 24. During the months of collecting data at both Elephant Mountain and Radio Hill, the ratio of monthly mean windspeed at the sites was a constant 0.58.

The seasonal pattern of mean windspeed at Elephant Mountain was also expected at Radio Hill. The highest estimated monthly mean windspeed was 15.5 mph in April. The lowest estimated mean speed was 6.0 mph in December. The estimated long-term annual mean windspeed for Radio Hill was 10.3 mph. The wind in 1981 fits the long-term estimate. Although March and April had a higher mean windspeed the the estimate, May, July, and August had a lower mean windspeed.

The best estimate of long-term mean windspeed at Radio Hill was slightly lower than the 1981 spring values, but slightly higher than the 1981 values for July and August. However it is possible that March and April 1981 are more representative of the long-term monthly mean windspeeds for the spring. In that case, the long-term annual mean windspeed for Radio Hill would be increased to 10.5 mph. Radio Hill was expected to have its highest value, 27 watts/ft^2, of monthly mean wind power in March, while the lowest wind power, 4.2 watts/ft^2, was expected in December. The estimated long-term annual mean wind power for Radio Hill was 13.5 watts/ft^2. The EPFs at Radio Hill were similar to those at Elephant Mountain. Winds during the spring and summer were steady while winds in the fall and winter varied. EPF's were slightly higher at Radio Hill than at Elephant Mountain. It is expected that these seasonal patterns will be repeated year after year. The principal wind direction at the Radio Hill site is west. Over 90% of the wind's energy is produced from winds originating from this quadrant.

The above analysis is for the Radio Hill site at the 30-foot level. Windspeeds at the hub height can be estimated from the power law:

$$U(H) = U(30)\left[\frac{(h + d)}{(30 + d)}\right]^{0.143}$$

where U(H) and U(30) are the mean windspeeds at hub height and 30 feet respectively, and d is a displacement. In flat terrain d = 0. In the case of Radio Hill, where the anemometer is located atop a small, steep hill, some of the wind passes to either side of the hill, which increases the height of the anemometer relative to the wind's profile. Determining the exact value of this upward displacement, d, is difficult without an on-site, multi-level measurement. A rough estimate of this displacement is d = 10 feet.

Using d = 10 feet, U(30) = 10.3 mph, and h = 80 feet and 100 feet, respectively, Equation (1) gives an estimated long-term annual mean windspeed of 11.6 mph at 80 feet and 11.9 mph at 100 feet. This information will be verified by the on-site wind resources measuring equipment presently located at Radio Hill. Additionally, this information will be used as a guide for testing the new 10-kW WECS at Radio Hill.

20-kW WECS Demonstration at Kaneohe Bay, Hawaii

A 20-kW WECS using a three-phase, line-commutated inverter was installed at the Marine Corps Air Station (MCAS), Kaneohe Bay, Hawaii, in September 1978 (Ref 10). This WECS system was a commercially designed, downwind, 2-kW wind-driven turbine with a synchronous inverter. The wind turbine had a three-phase alternator driven by a three-bladed rotor, 24 feet in diameter. The system was mounted on a free-standing, reinforced concrete tower approximately 38 feet in height and was designed to produce 20 kW of power at a rated windspeed of 29 mph. The WECS was configured to supply power to an instrumentation shop. The WECS system installation is shown in Figure 25. A plot of power output versus windspeed is shown in Figure 26, and the design characteristics are listed in Table 8.

Test results from this WECS have yielded the following information. The system had numerous technical problems. The electronic control unit (ECU) failed three times during the test. The synchronous inverter fuses were also blown. No more problems were observed with the synchronous inverter after a 27-kVA isolated transformer was placed between the inverter and the grid. Based on this experience, one recommendation is to avoid using a complicated control system such as the ECU. The ECU is too complicated in design and very unreliable. However, if such a system must be used, spares should be kept available for easy repair and shorter downtime.

The test results, based on 3.5 years of testing, indicated that the WECS at Kaneohe Bay had a MTBF of 61 days. This low value for the MTBF is attributed to the prototype nature of the WECS design that used the complicated electronic controls. Over the past few years, wind turbine technology has advanced considerably and some WECS designs with improved MTBF values are now available. In January 1983 the 20-kW WECS at Kaneohe Bay was replaced by such a system with a 12-kW output rating. The new WECS is currently undergoing field tests to gather performance, operating, and maintenance data.

12-kW Grid-Integrated, High Reliability WECS Demonstration at Kaneohe Bay, Hawaii

The 12-kW WECS installed at Kaneohe Bay is shown in Figure 27, and the design characteristics are listed in Table 9. The test, which is still in progress, has shown that the machine is reliable with no problems. Good points of this machine include the absence of slip-rings and bearings, and the ability to function in winds up to 100 mph. Figure 28 shows the generator's output versus windspeed.

This WECS is still undergoing field testing to obtain the following information:

(a) Operation, maintenance, and performance data of the WECS
(b) System reliability
(c) Economics of such power sources

DISCUSSION

As shown by the field tests, it is evident that most of the WECS available today are plagued with failures that result in low availability. Two exceptions are the 2-kW WECS at Port Hueneme and the 12-kW WECS at Kaneohe Bay, Hawaii, which have about a 90% system availability. The failures were attributed to design errors (ignorance of natural laws, including inexperience in the overall concept of wind turbine technology). This is particularly true of the WECS manufactured by small companies, which lack knowledge in either aerodynamics, electrical machines, or electronic controls, including basic mechanical designs, by underestimating the tremendous dynamic forces generated by atmospheric turbulence. It should also be noted that these WECS were operated in severe environmental condition (e.g., salt spray, blowing sand, grit, etc.) and in most cases the design did not always consider these factors. As a result, there are only three manufacturers who market reliable WECS in the 1-to-40 kW range. The main design features of a reliable WECS are:

Rotor

A good rotor should use fixed-pitch blades. The low extra output available from variable-pitch blades is more than offset by the downtime created with the variable-pitch mechanism and maintenance requirements. Fixed-pitch blades can be attached to the main shaft, and can be set at the factory for perfect dynamic balance.

Bearings

The fatigue life of most roller bearings used in WECS is about 50,000 hours. It is, therefore, concluded that the bearings of WECS system will have to be changed every 4 to 5 years as part of a preventive maintenance program.

Yaw System

A yaw control provided through a tail-vane or simply a downwind machine controlled by the wind is undesirable. This type of yaw control responds instantly to the always changing, wind direction. Because of the inertia-gyroscopic effect generated by the turning rotor, tremendous forces, thus stresses, are generated on the blades. This fatigues the yaw shaft, until it finally breaks off, destroying the entire WECS and perhaps causing other safety hazards.

Smaller machines, which generally do not suffer from gyro-induced stresses, are currently equipped with a side vane, to turn the turbine away from the wind if it is blowing too hard. However, a turbine oriented at a certain angle to the wind results in a different angle of attack, two times per revolution of every blade. This means that the mechanical forces on the blades are reversed twice during every revolution, again inducing extreme fatigue on the blades. Hence, a good WECS rotor must be designed to generate power at all windspeeds up to its survival speed.

Certain WECS designs available now employ extra small tail-rotors that start running when hit by a side wind. These running rotors are geared down some 2,000 to 4,000 times before yawing the nacelle. Not only are the gyro effects insignificant, due to the very slow yaw movements, but the prop yaws the heavy nacelle into the wind much earlier (with lower windspeeds) than other systems that rely on pure wind forces.

As a result of the above discussion, it is clear that a wind machine should never be turned away from the wind. Always keep it in the wind completely. Even more, do not shut it down because of high winds; a running mill presents resistance than one shut down (unless completely feathered).

Slip-Rings

If possible, do not use slip-rings because of increased maintenance. There are some WECS on the market that do not use slip-rings. Eliminating the slip-rings increases the WECS's availability and reliability.

CONCLUSIONS

The results of NCEL's investigation to date lead to following conclusions:

1. The WECS rotor must use fixed-pitch, nonmetallic blades with an upwind configuration.

2. The electric generator must be a low-speed, permanent-magnet type that has variable speeds and eliminates the use of gearboxes.

3. Avoid using complicated control systems, such as the ECU. If they are used spares should be kept on hand.

4. If at all possible, slip-ring and bearing must be eliminated.

5. All the controls must be passive and fail safe.

6. The tower must be guyed and hinged for easy maintenance.

7. All bearings should be sealed and self-lubricating.

FUTURE TRENDS

There are some manufacturers who are designing and marketing small WECS with the desirable design features discussed in this report. NCEL's current experience with nine systems indicate a definite improvement in WECS's reliability and availability. Efforts are underway at the Laboratory to gather data on the operation and maintenance characteristics of such systems in an application mode.

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Table 1. Specifications for 2-kW, Upwind, Horizontal Axis WECS at NCEL, Port Hueneme, California

Item	Value
Rotor	
Diameter	12.5 ft
Capture area	122.7 ft^2
Blade materials	Stainless steel
Number of blades	3
Rotor solidity	10.0%
Rotational speed	130-180 rpm
Cut-in windspeed	10 mph
Cut-out windspeed	None
Rated windspeed	25 mph
Survival windspeed	100 mph
Overspeed control latching	Centrifugal governor with magnetic
Transmission	
Type	Planetary gear stepup
Gear ratio	5.1
Generator	
Type	Self-excited brushless rotor
Number of poles	8
Rated voltage	220 volts, 3-phase
Power form	3-phase variable frequency, 43-60 Hz
Rated power	2 kW at 25 mph, 3 kW at 30 mph
Power curve	See Figure 7
Field slip-rings	None
Yaw slip-rings	Five similar aero-motive type
Tower	
Type	Open-truss, free standing
Height	60 ft
Protective coatings	Heavy galvanized
Power Conditioning	
Generic type	Automatic load matching with relays for switching loads
Features	Load relays are operated with commercial control modules
Site Information	
Annual average windspeed	6.5 mph
Corrosion potential	High
Environmental extremes	Heavy saltwater spray

Table 2. Specifications for 5-kW, Upwind, Horizontal Axis San Nicolas Island, California

Item	Value
Rotor	
Diameter	16.42 ft
Capture area	211.7 ft^2
Blade materials	Laminated wood
Number of blades	3
Rotor solidity	5%
Rotational speed	100-200 rpm
Cut-in windspeed	8 mph
Cut-out windspeed	45 mph
Rated windspeed	24 mph
Survival windspeed	100 mph
Overspeed control	Centrifugal governor
Transmission	
Type	Planetary gears, stepup
Gear ratio	4.12
Generator	
Type	Self-excited with field brushes
Number of poles	16
Rated voltage	190 volts, 3 phase
Power form	3-phase variable frequency 55-110 Hz
Rated power	5 kW
Power curve	See Figure 9
Field slip-rings	2
Yaw slip-rings	3
Tower	
Type	Open-truss guyed
Height	50 ft
Protective coatings	Heavy galvanized
Power Conditioning	
Generic type	Automatic load matching with switching loads
Features	Load relays are operated with commercial control modules
Site Information	
Annual average windspeed	15 mph
Corrosion potential	Very high
Environmental extremes	High corrosion potential, high humidity

Table 3. Specifications for 6-kW, WECS, Upwind, Horizontal, Axis at Treasure Island, California

Item	Value
Rotor	
Diameter	17.42 ft
Capture area	238.371 ft^2
Blade material	Laminated wooden blades without twist
Number of blades	3
Rotor solidity	5.2%
Rotational speed	100-200 rpm
Cut-in windspeed	8 mph
Cut-out windspeed	45 mph
Rated windspeed	28 mph
Survival windspeed	100 mph
Overspeed control	Centrifugal governor
Transmission	
Type	Planetary gears, stepup
Gear ratio	4.12
Generator	
Type	3-phase, permanent-magnet rotor
Number of poles	16
Rated voltage	140 volts
Power form	DC
Rated power	6 kW
Power curve	See Figure 13
Field slip-rings	None
Yaw slip-rings	3
Rotational speed	412-824 rpm
Tower	
Type	Open truss, free standing
Height	60 ft
Protective coatings	Heavy galvanized
Power Conditioning	
Generic type	Single-phase, line-commutated inverter
Features	120 volts AC (rated voltage) 7.5 kW (rated power output)
Site Information	
Average available power in the wind	4-5 watts/ft^2
Annual average windspeed	8-10 mph
Corrosion potential	Not very severe
Environmental extremes	Not significant

Table 4. Specifications for 9-kW Downwind, Horizontal Axis WECS, at NEW, China Lake, California

Item	Value
Rotor	
Diameter	32.8 ft
Capture area	845.0 ft^2
Blade material	Straight section extruded aluminum with twisted and tapered fiberglass tip
Number of blades	3
Rotor solidity	4%
Rotational speed	65 to 160 rpm
Cut-in windspeed	9 mph
Cut-out windspeed	45 mph
Rated windspeed	20 mph
Survival windspeed	125 mph
Overspeed control	Hydraulic governor
Transmission	None
Generator	
Type	Permanent magnet, 3-phase alternator
Number of poles	58
Rated voltage	240 volts
Power form	3-phase, AC
Rated Power	9 kW
Power curve	See Figure 16
Field slip-rings	None
Yaw slip-rings	3
Rotational speed	0 to 160 rpm
Tower	
Type	Hinged tubular, guyed with a winch and A-frame
Height	55 ft
Protective coatings	Galvanized
Power Conditioning	
Generic type	Solid-state, constant frequency inverter
Features	120 VAC (rated voltage) 9.5 kW (rated power output)
Site Information	
Average available power in the wind	6.5 watts/ft^2
Annual average windspeed	6.6 mph
Corrosion potential	None
Environmental extremes	Blowing sand and grit

continued

Table 4. Continued

Item	Value
Storage System	
Type	57 lead acid 2.1 volt cells connected in series. (Note: The cells are heavy duty lead-acid batteries with tubeless cathodes with a charge rating of 930 ampere-hours.)

Table 5. Specifications for 10-kW Upwind, Horizontal Axis WECS at Radio Hill, Barstow, California

Item	Value
Rotor	
Diameter	24.3 ft
Capture area	491 ft^2
Blade material	Steel
Number of blades	3
Rotor solidity	9%
Rotational speed	80 to 85 rpm
Cut-in windspeed	9 mph
Cut-out windspeed	60 mph
Rated windspeed	25 mph
Survival windspeed	100 mph
Overspeed control	Centrifugal governor
Transmission	
Type	Planetary gearbox, step up
Gear ratio	18
Generator	
Type	3-phase induction generator
Number of poles	4
Rated voltage	240 volts
Power form	3-phase, AC
Rated power	10 kW
Power curve	See Figure 20
Field slip-rings	None
Yaw slip-rings	3
Rotational speed	80 to 85 rpm
Tower	
Type	Free-standing truss-type
Height	40 ft
Protective coatings	Galvanized
Power Conditioning	None
Site Information	
Average available power in the wind	18.0 watts/ft^2
Annual average windspeed	10.8 mph
Corrosion potential	None
Environmental extremes	Blowing sand and grit

Table 6. Specifications for the New 10-kW Upwind, Horizontal Axis Radio Hill, Barstow, California

Item	Value
Rotor	
Diameter	23.0 ft
Capture area	416 ft^2
Blade material	Pultruded fiberglass
Number of blades	3
Rotor solidity	6%
Rotational speed	60-350 rpm
Cut-in windspeed	8 mph
Cut-out windspeed	35 mph
Rated windspeed	28 mph
Survival windspeed	120 mph
Overspeed control	Centrifugal governor
Transmission	None
Generator	
Type	Permanent magnet alternator
Number of poles	20
Rated voltage	120 volts DC
Power form	3-phase, AC
Rated power	10 kW
Field slip-rings	None
Yaw slip-rings	3
Tower	
Type	Truss, free standing
Height	40 ft
Protective coatings	Galvanized
Power Conditioning	
Generic type	Single phase line commutated input
Features	120 volts DC and output 240 volts AC, 60 Hz
Site Information	
Annual average windspeed	10.8 mph
Corrosion potential	None
Environmental extremes	Blowing sand and grit

Table 7. Estimated Windspeed, Power, and Energy Pattern Factor for Radio Hill During 1981

Month	Windspeed (mph)	Power (watts/ft^2)	EPF
Jan	6.4	4.7	3.3
Feb	8.2	9.2	3.1
Mar	14.3	27.0	1.7
Apr	15.5	26.3	1.3
May	15.1	22.5	1.2
Jun	13.1	19.6	1.6
Jul	11.3	14.1	1.8
Aug	9.9	10.0	1.9
Sep	8.8	8.2	2.2
Oct	7.8	10.1	3.9
Nov	6.8	6.6	3.9
Dec	6.0	4.2	3.6
Annual	10.3	13.5	2.3

Table 8. Specifications for 20-kW, Downwind, Horizontal Axis WECS at Kaneohe Bay, Hawaii

Item	Value
Rotor	
Diameter	25.0 ft
Capture area	491 ft^2
Blade material	Aluminum
Number of blades	3
Rotor solidity	8%
Rotational speed	0 to 100 rpm
Cut-in windspeed	8 mph
Cut-out windspeed	60 mph
Rated windspeed	29 mph
Survival windspeed	100 mph
Overspeed control	Centrifugal mechanical governor
Transmission	
Type	Planetary gears
Gear ratio	18.1
Generator	
Type	Three-phase with a rectifier to produce DC output compatible with a synchronous inverter
Number of poles	4
Rated voltage	220 volts
Power form	3-phase, variable frequency
Rated power	20 kW at 29 mph windspeed
Power curve	See Figure 26
Field slip-rings	2
Yaw slip-rings	5
Tower	
Type	Free-standing, cylindrical concrete
Height	40 ft
Protective coatings	None
Power Conditioning	
Generic type	Single-phase, line-commutated inverter
Features 220	220 volts AC (rated voltage) 20 kW (rated power output)
Site Information	
Average available power in the wind	14.3 watts/ft^2
Annual average windspeed	12 mph
Corrosion potential	Very high
Environmental extremes	None

Table 9. Specifications for 12-kW High Reliability, Upwind, Horizontal Axis at Kaneohe Bay, Hawaii

Item	Value
Rotor	
Diameter	23.0 ft
Capture area	415 ft^2
Blade material	Laminated wood
Number of blades	3
Rotor solidity	5.2%
Rotational speed	205 rpm (peak)
Cut-in windspeed	8 mph
Cut-out windspeed	None
Rated windspeed	27 mph
Survival windspeed	100 mph
Overspeed control	Centrifugal
Transmission	
Type	Offset-hypoid gear
Gear ratio	6.1
Generator	
Type	25-kW brushless alternator
Number of poles	6
Rated voltage	180 volts
Power form	3-phase, AC
Rated power	12.5 kW at mph windspeed
Power curve	See Figure 28
Field slip-rings	2
Yaw slip-rings	None
Tower	
Type	Free-standing, cylindrical concrete
Height	40 ft
Protective coatings	None required
Power Conditioning	
Generic type	1-phase, (228-252 volts AC), 60 Hz line-commutated inverter with SCRs
Features	15 kW (rated power output)
Site Information	
Average available power in the wind	14.3 watts/ft^2
Annual average wind speed	12 mph
Corrosion potential	Very high
Environmental extremes	None

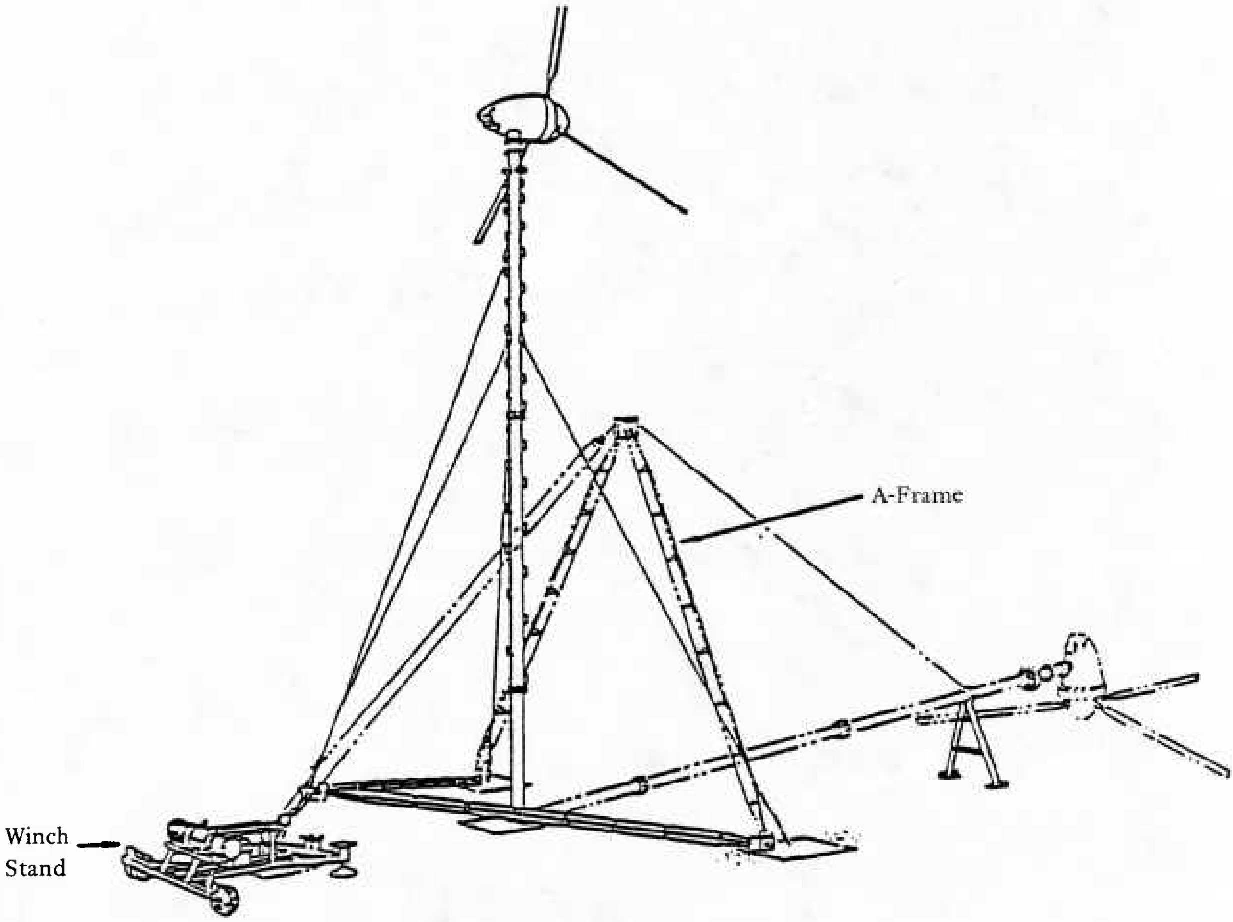

Figure 1. Erecting a hinged tower using a winch and A-frame.

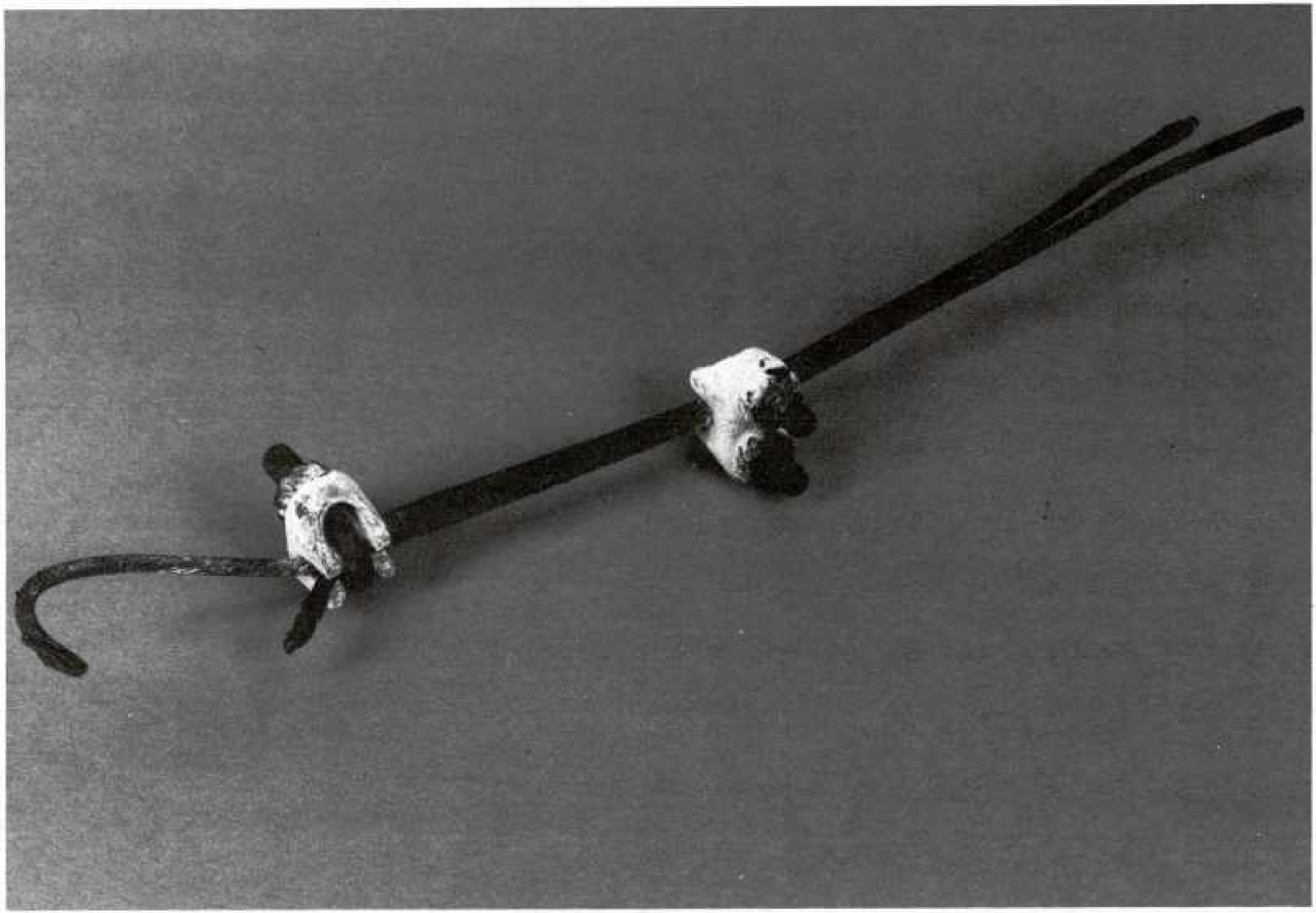

Figure 2. Corroded steel guy wire, MCAS, Kaneohe, Hawaii.

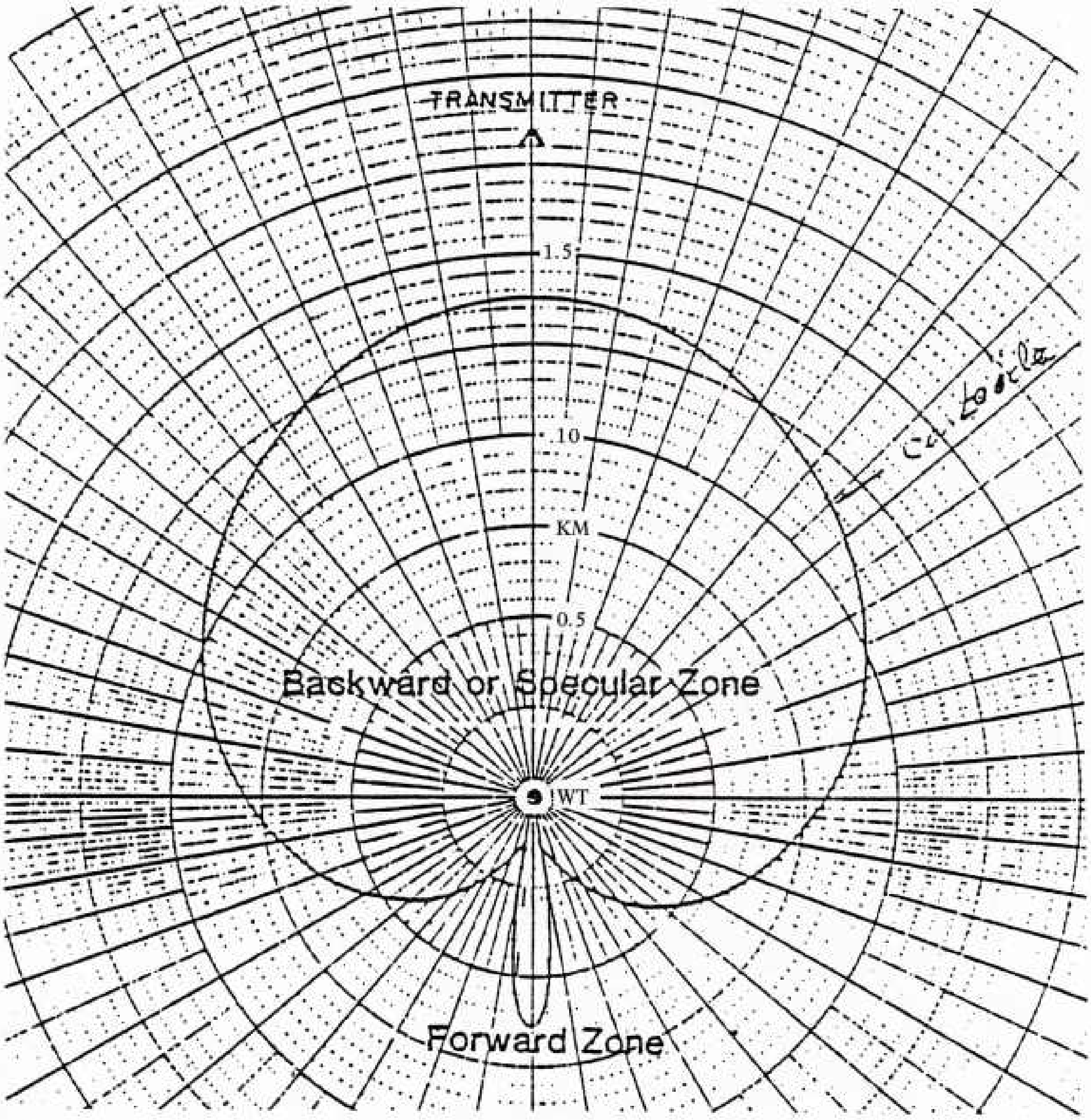

Figure 3. Typical interference zones--television bands. (WECS size 200-kW, rotor diameter 125 feet.)

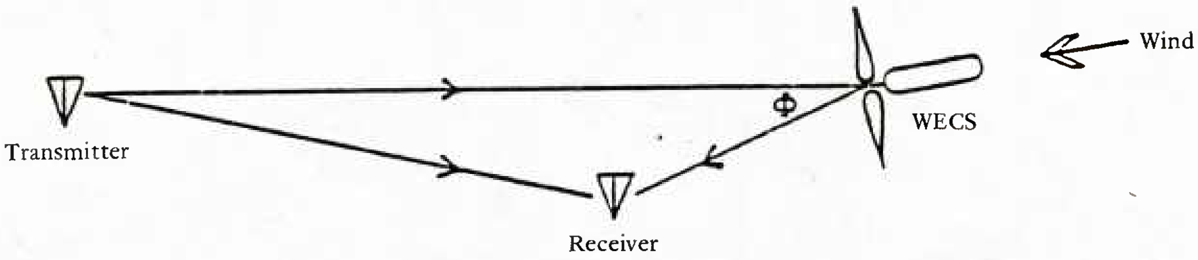

Figure 4. WECS television interference geometry.

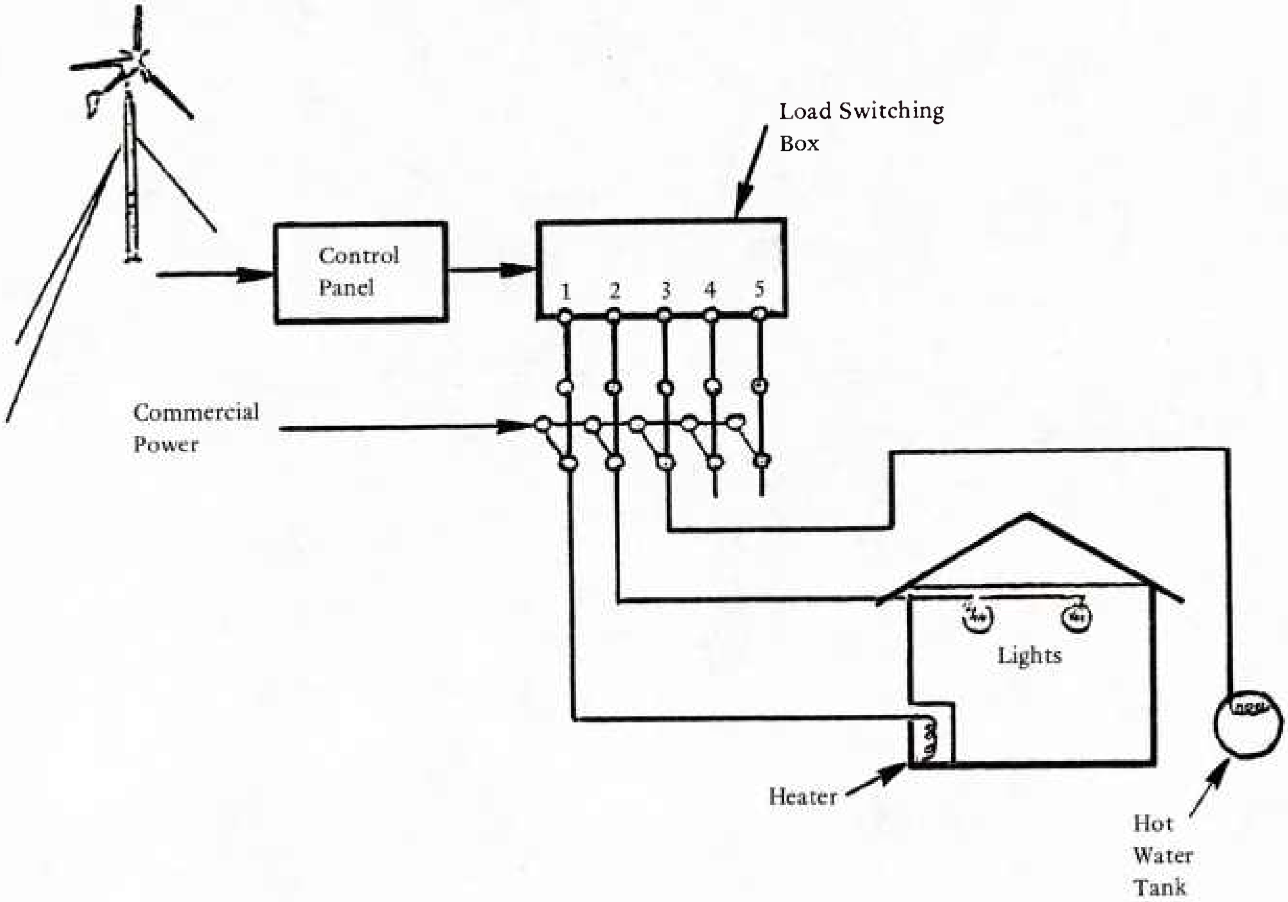

Figure 5. Automatic load matching system schematic for WECS.

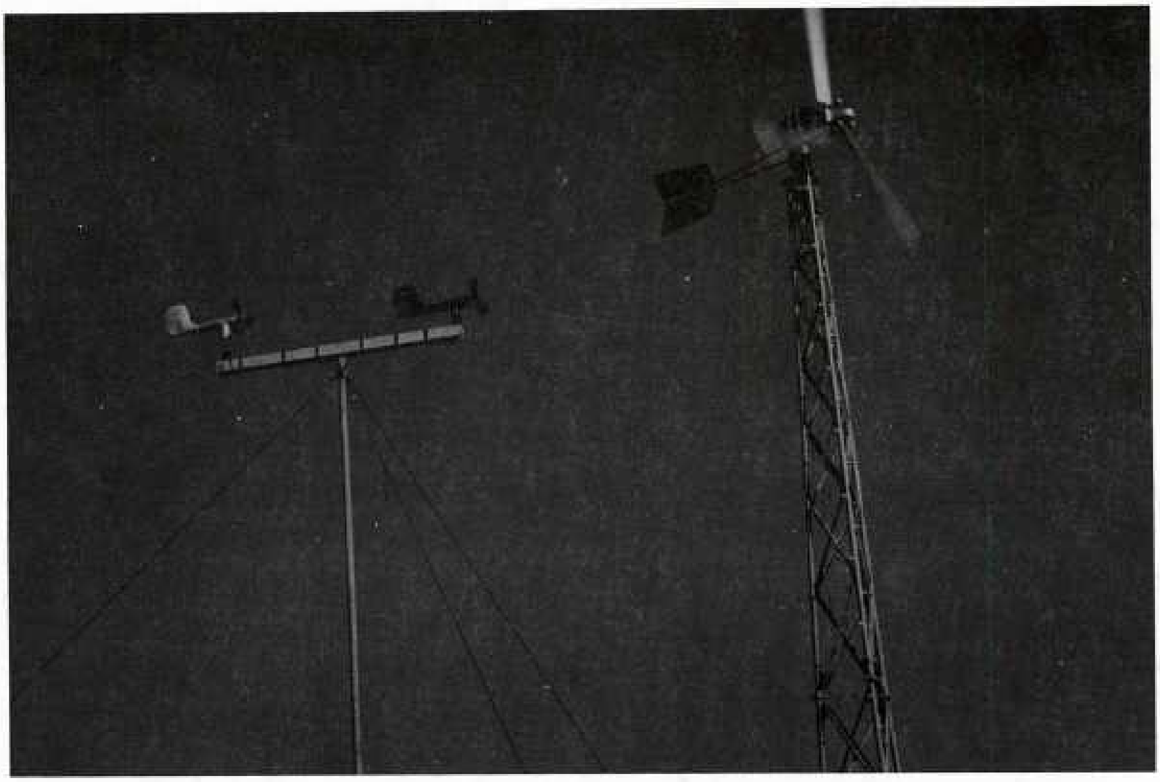

Figure 6. 2-kW WECS with an automatic load matching system.

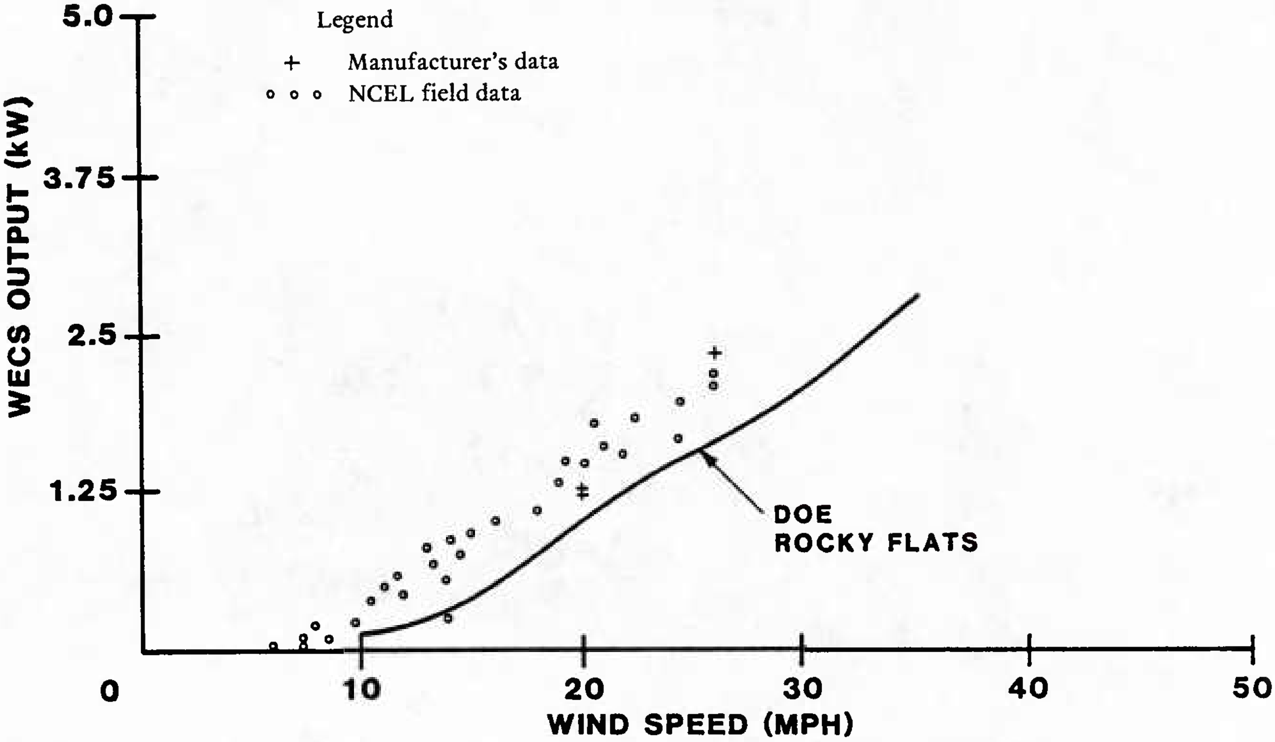

Figure 7. Performance curve for 2-kW WECS at NCEL, Port Hueneme.

Figure 8. 5-kW WECS installed at San Nicolas Island.

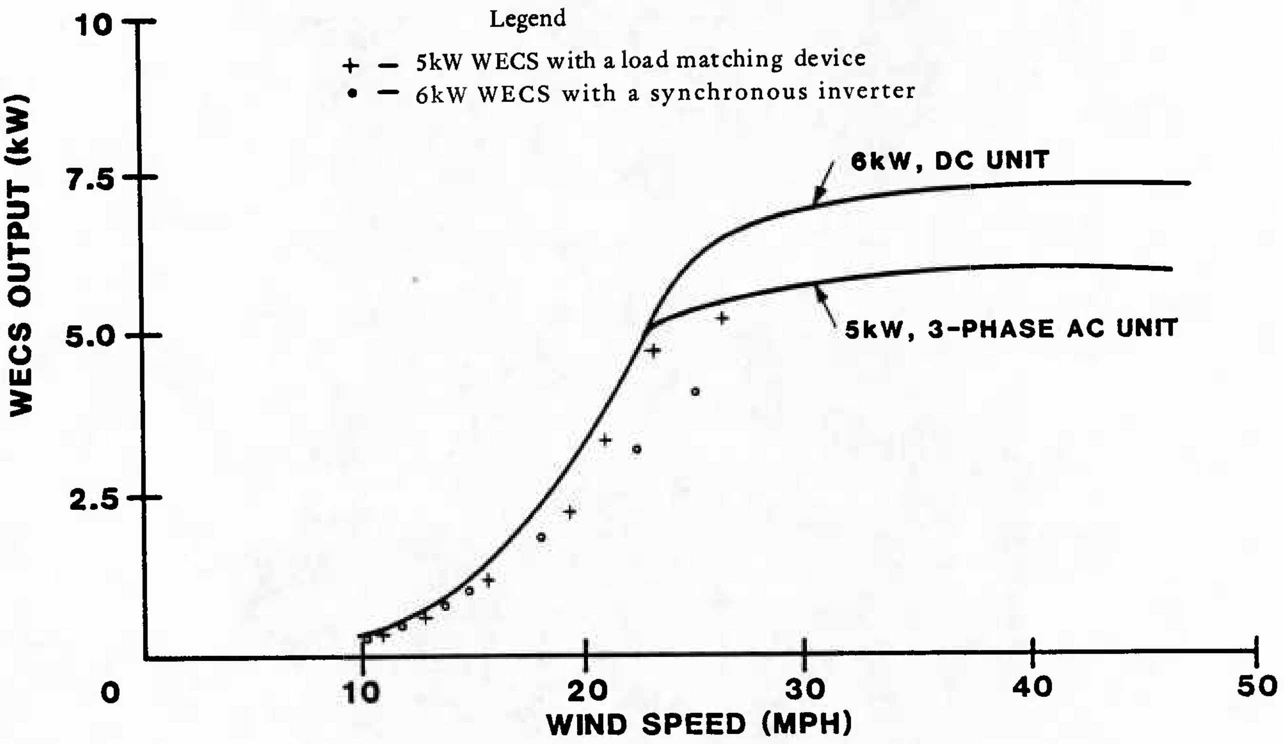

Figure 9. Performance curve for 5-kW WECS at San Nicolas Island.

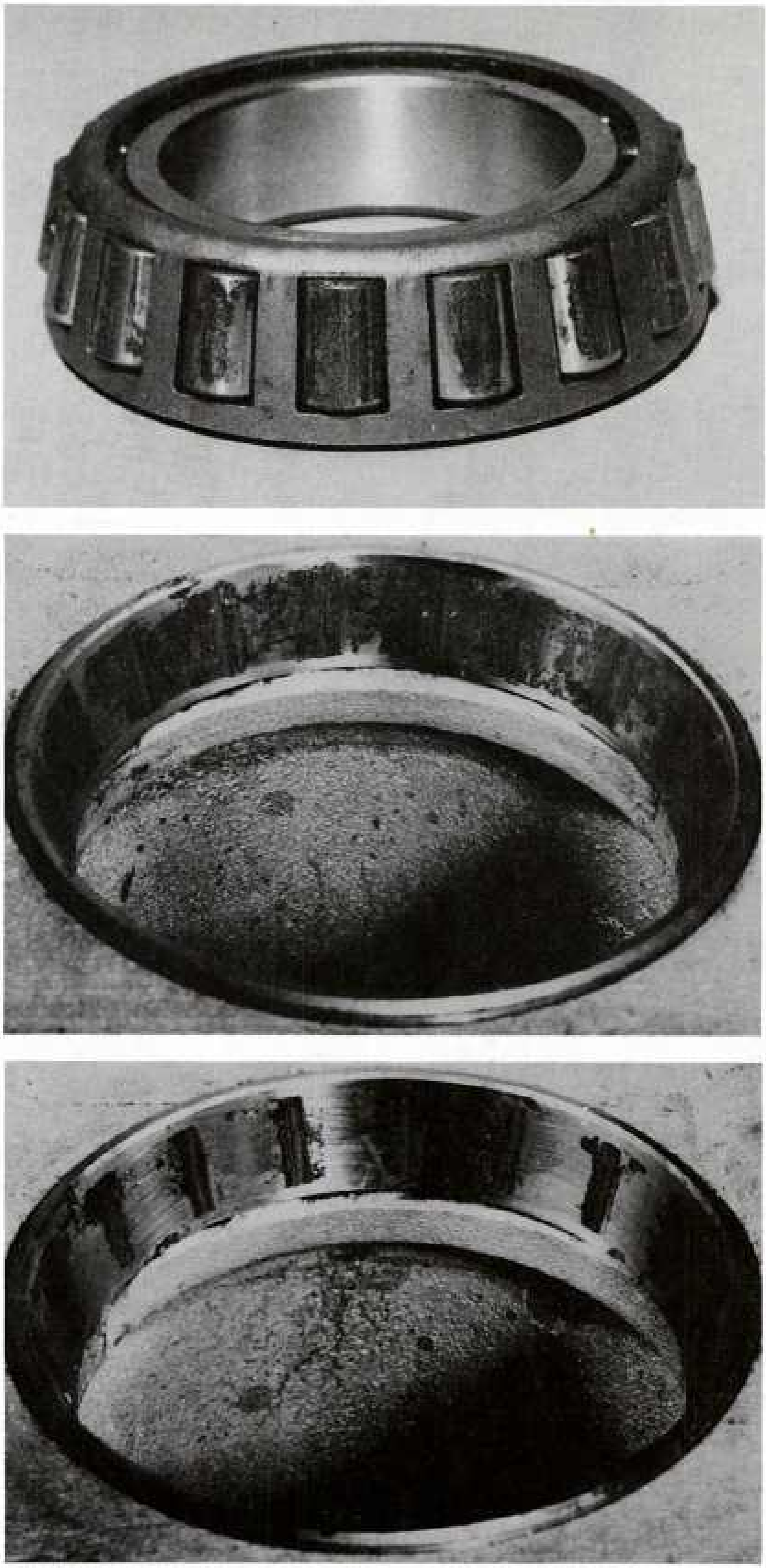

Figure 10. Corroded 5-kW WECS bearings.

Figure 11. 6-kW WECS installed at Naval Station, Treasure Island.

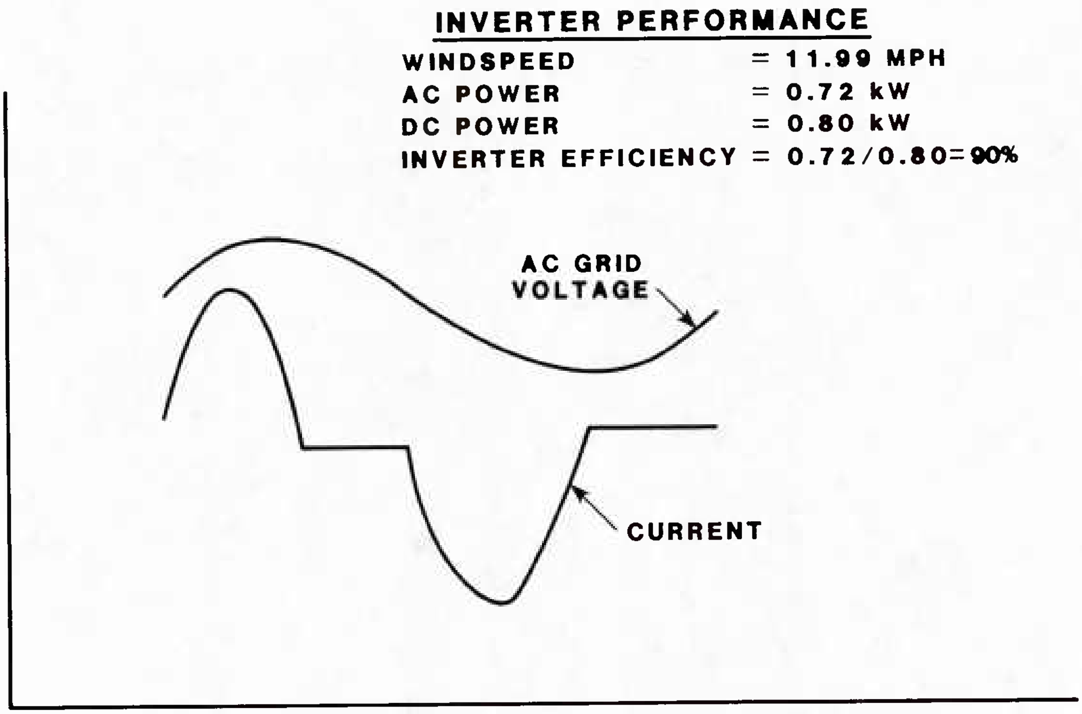

Figure 12. Synchronous inverter output waveforms at Naval Station, Treasure Island.

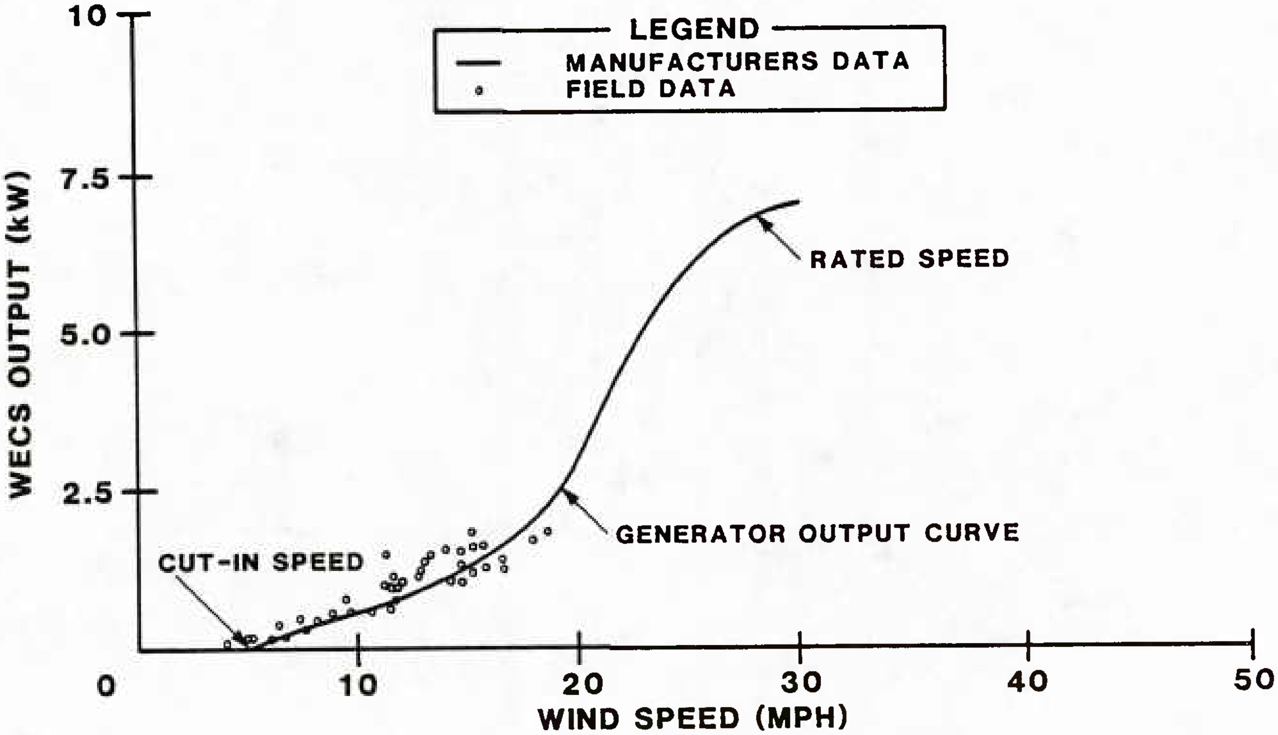

Figure 13. Performance curve of the 6-kW WECS with a synchronous inverter.

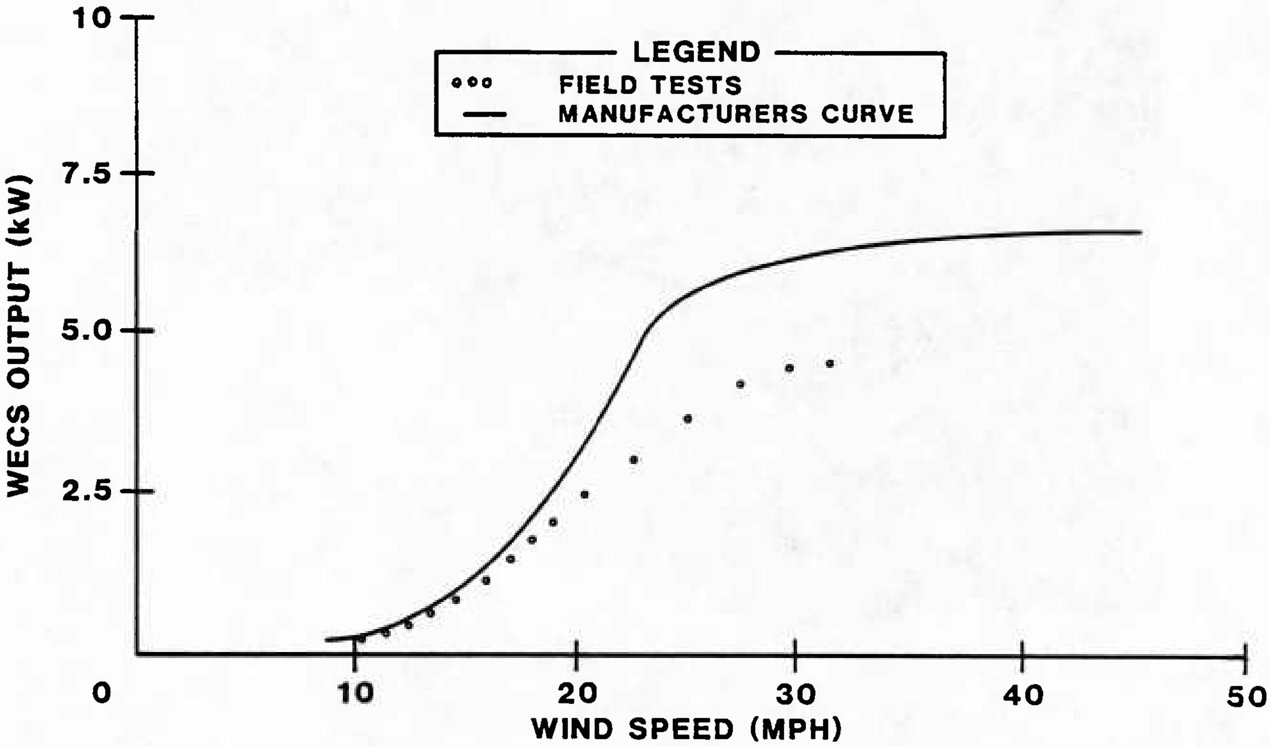

Figure 14. Performance curves for 6-kW WECS at San Nicolas Island.

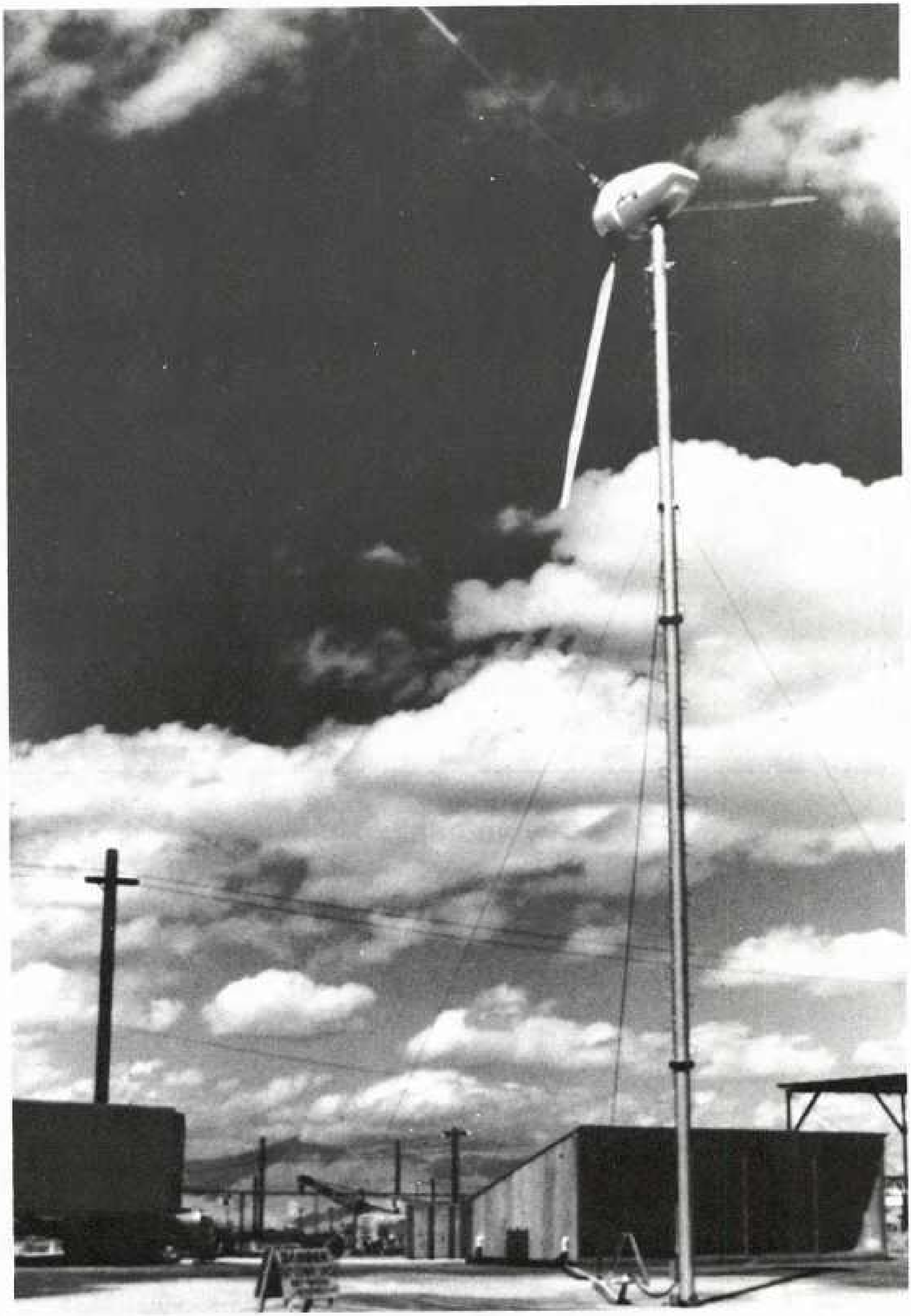

Figure 15. 9-kW WECS installed at NWC, China Lake.

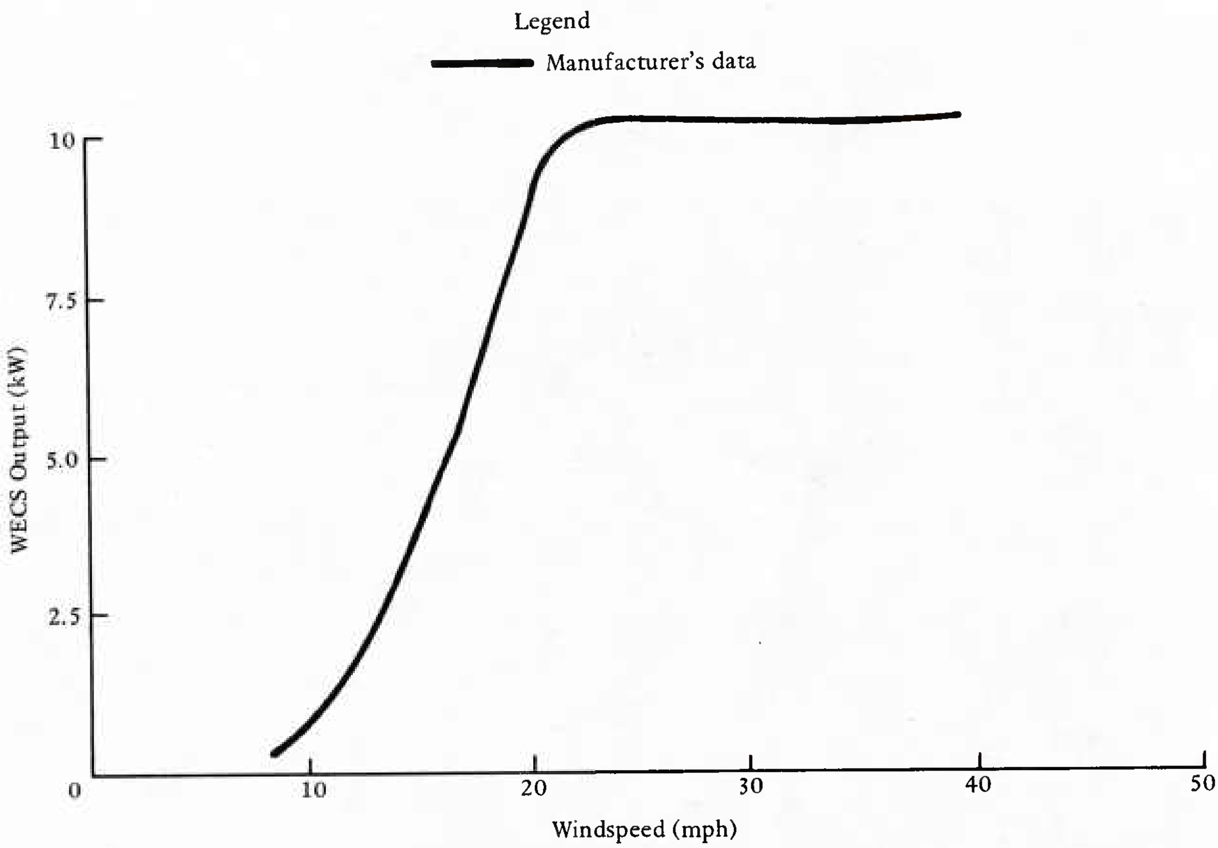

Figure 16. Performance curve for the 9-kW WECS at NWC, China Lake.

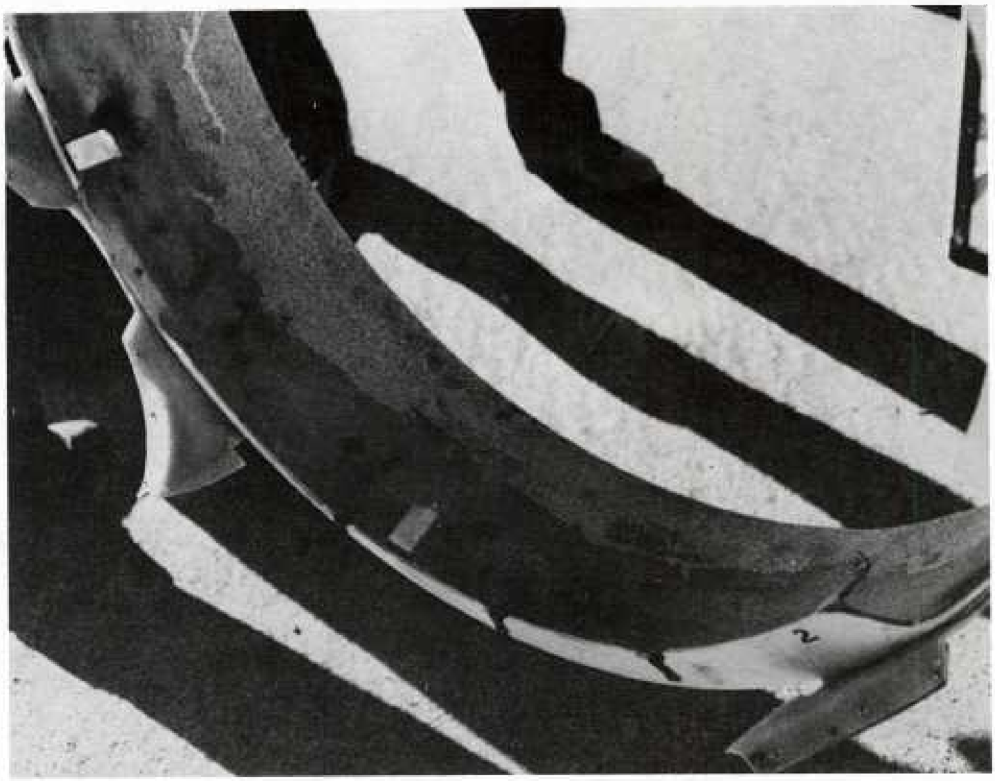

Figure 17. 9-kW WECS's damaged shroud.

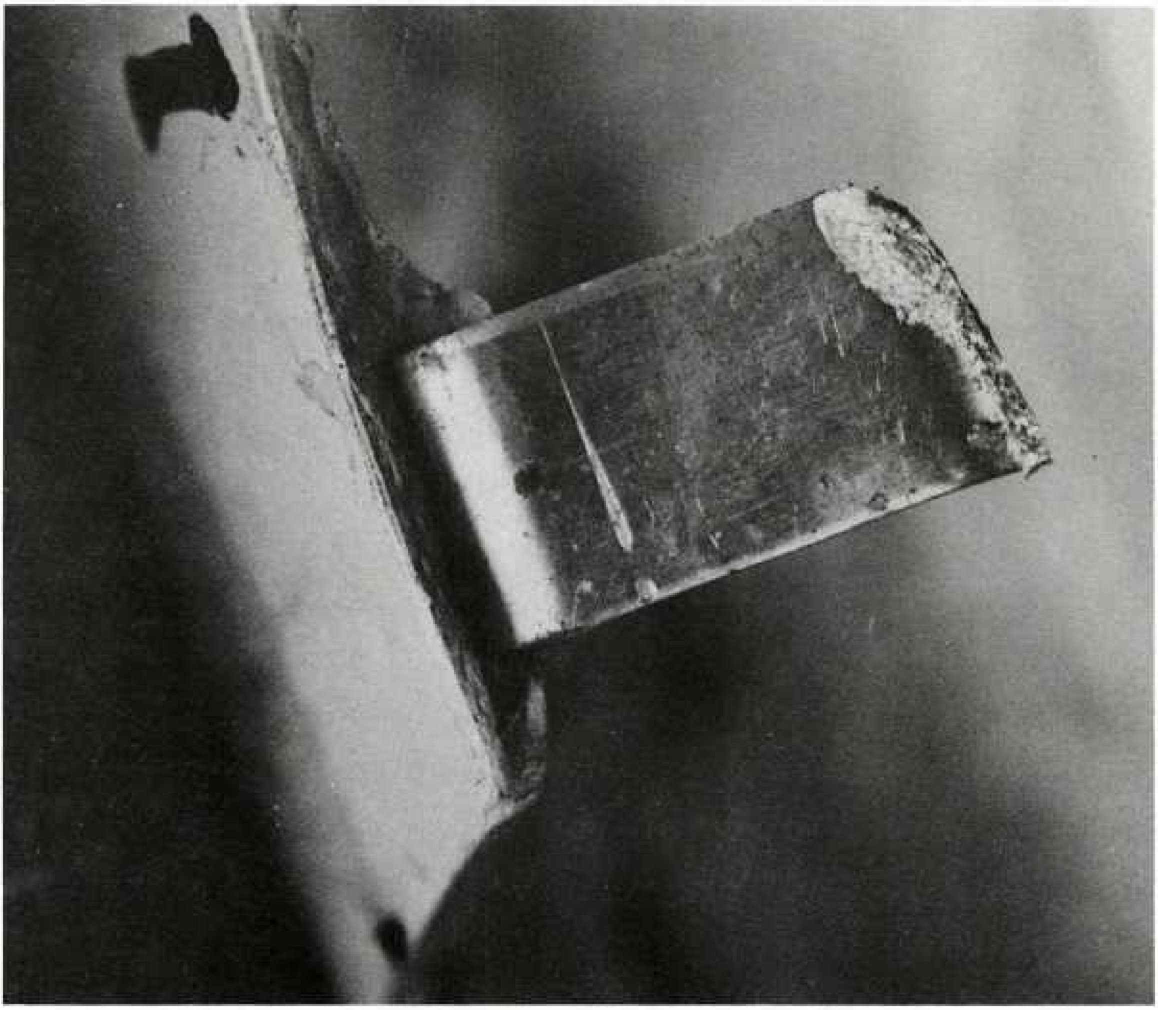

Figure 18. 9-kW WECS's sheared brace.

Figure 19. 10-kW WECS installed at MCLB, Barstow.

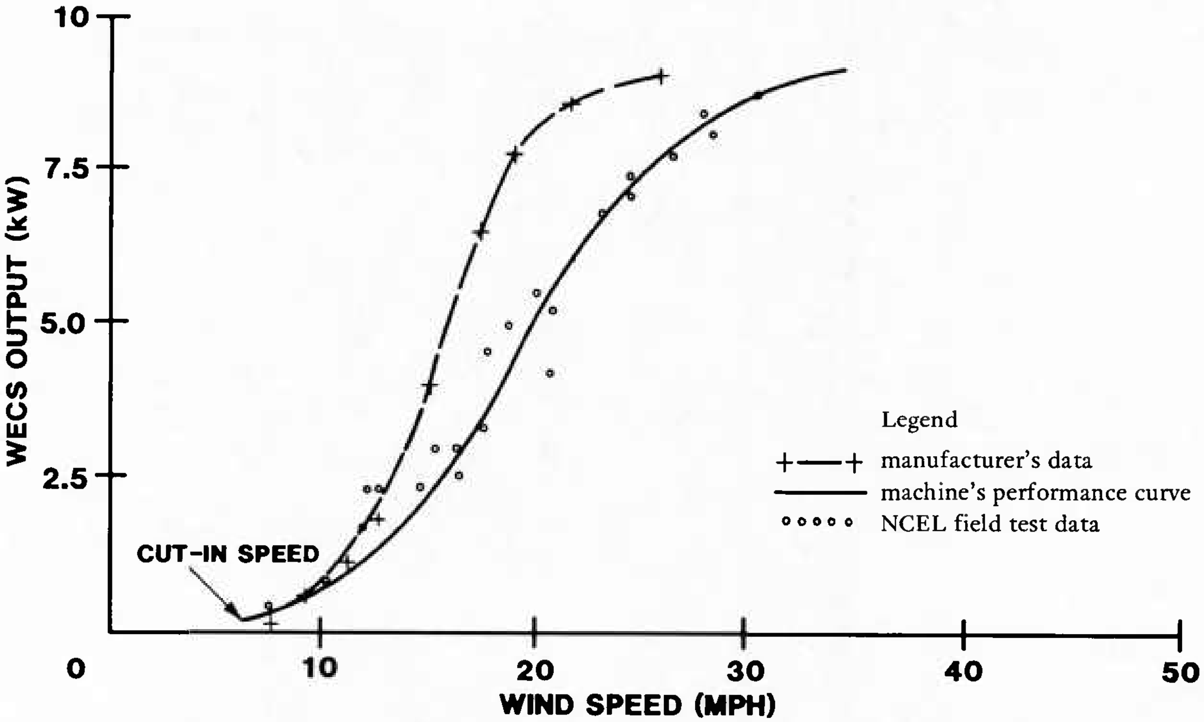

Figure 20. Performance curves for 10-kW WECS.

Figure 21. 10-kW WECS's damaged rotor.

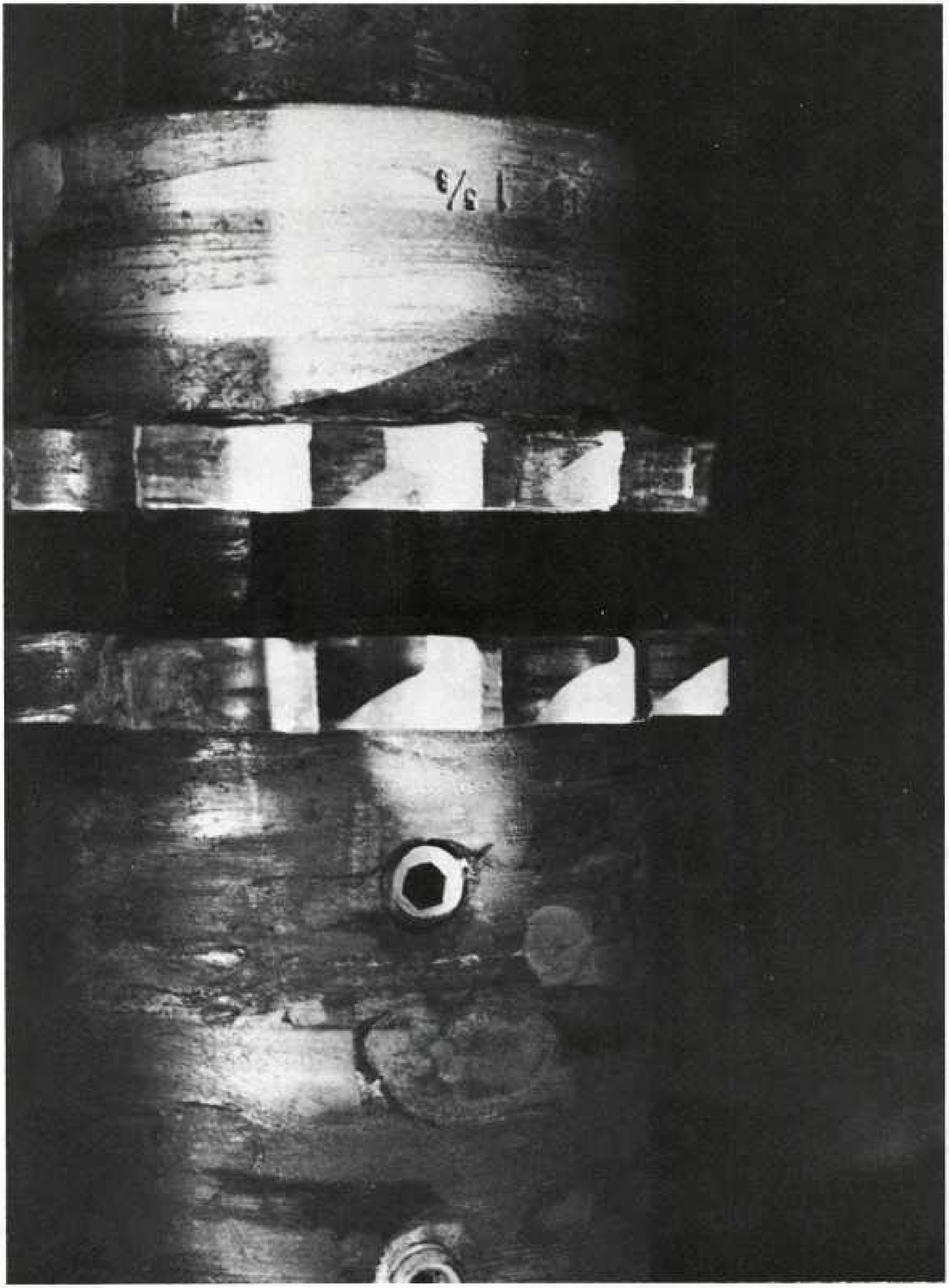

Figure 22. Damaged coupling machine (link chain removed).

Figure 23. New 10-kW WECS installed at MCLB, Barstow.

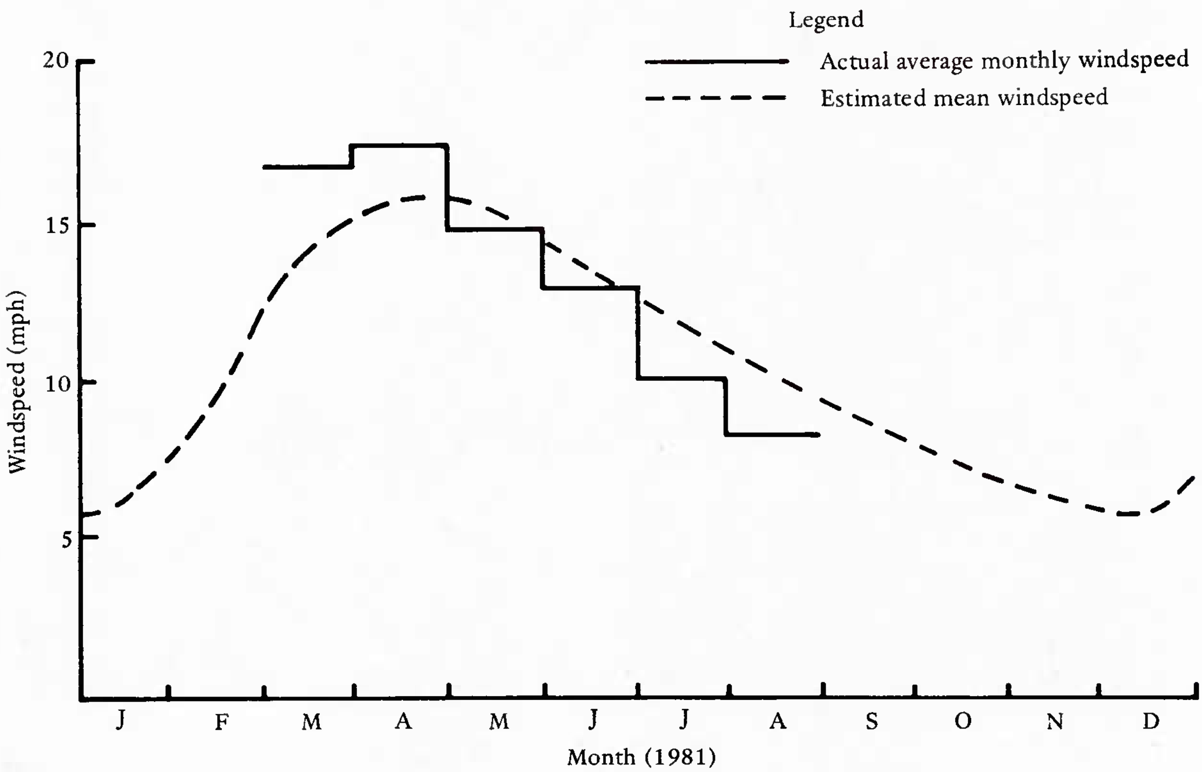

Figure 24. Estimated monthly mean windspeed for Radio Hill.

Figure 25. 20-kW WECS installed at MCAS Kaneohe Bay, Hawaii.

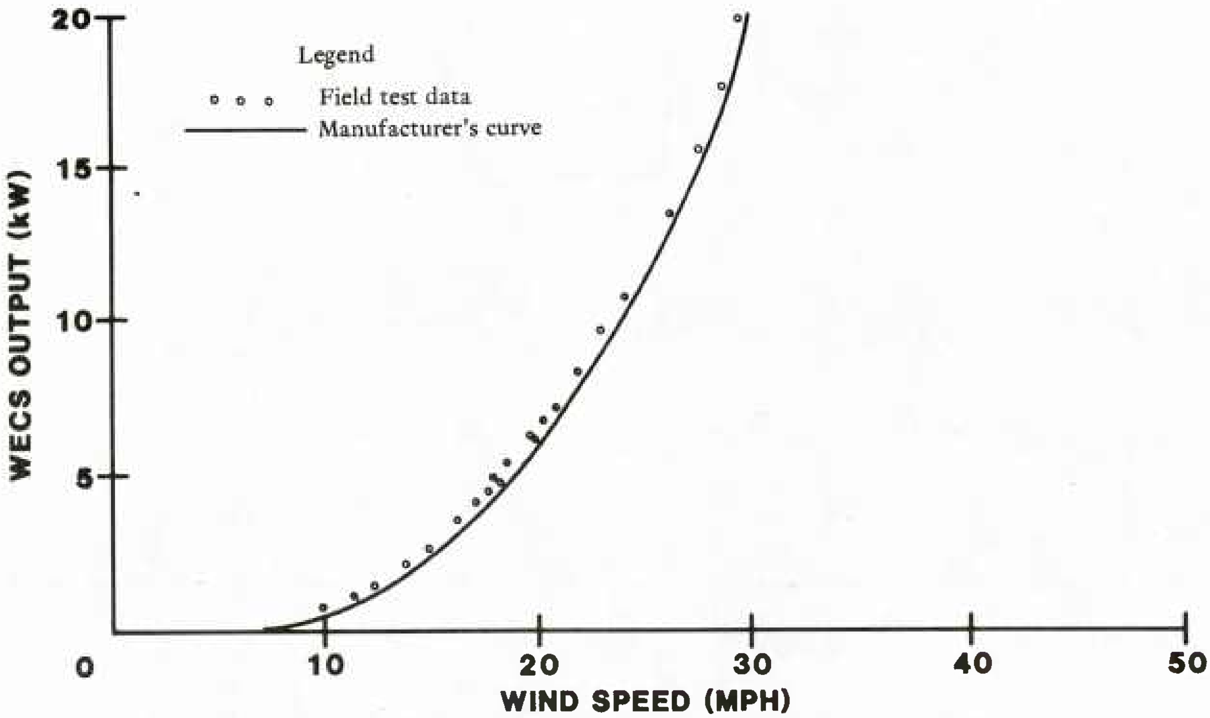

Figure 26. Measured performance curve of the 20-kW WECS.

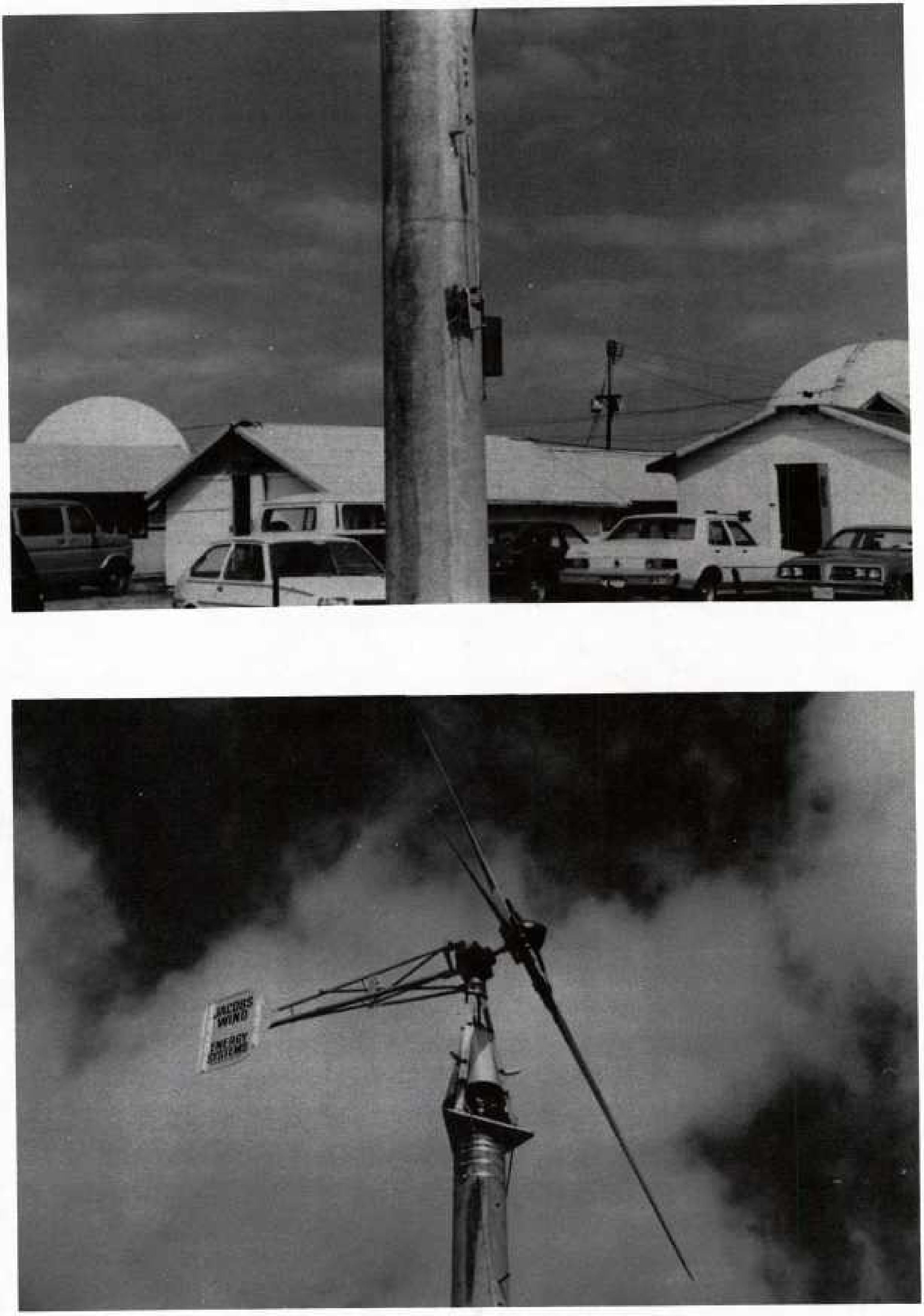

Figure 27. 12-kW WECS installed at Kaneohe Bay, Hawaii.

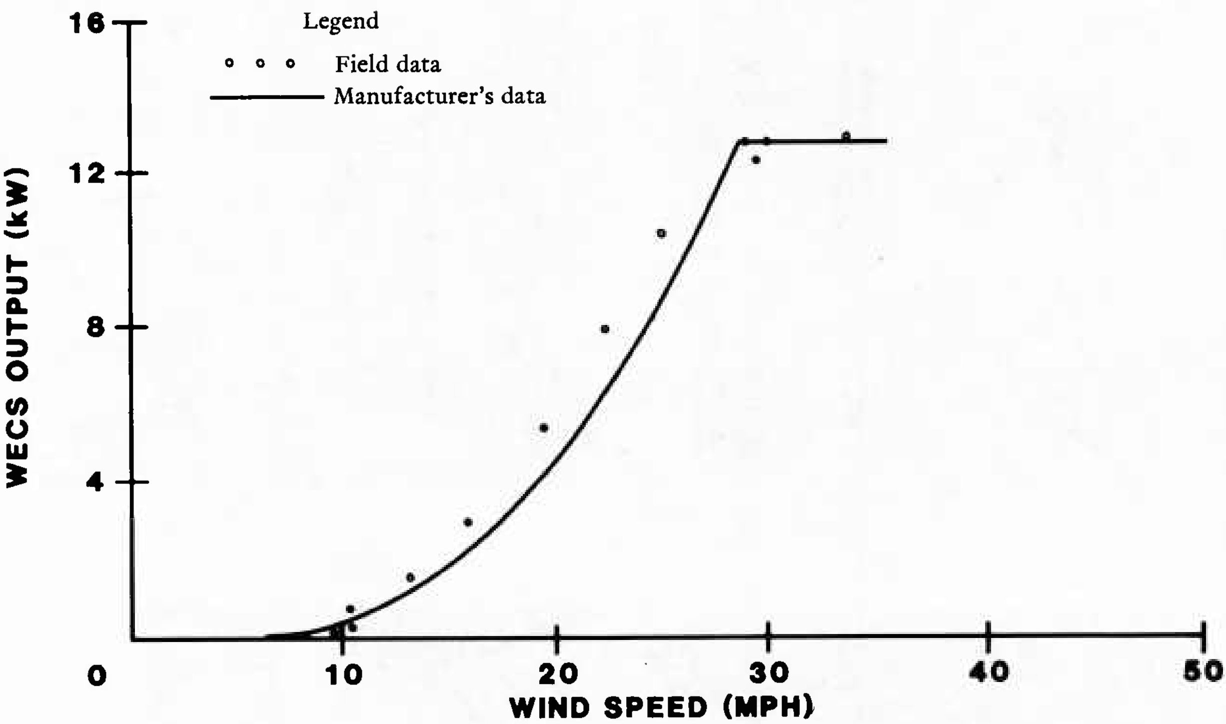

Figure 28. Output versus wind speed characteristics of the 12-kW WECS.

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